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(54) **FUEL INJECTION SYSTEM**

KRAFTSTOFFEINSPRITZSYSTEM

SYSTÈME D'INJECTION DE CARBURANT

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(56) References cited:
US-A1- 2005 263 135
US-A1- 2006 097 067
US-A1- 2007 095 934
US-A1- 2009 108 093
US-A1- 2010 236 526
US-B1- 6 422 836

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Description

BACKGROUND

[0001] The present application relates generally to the field of internal combustion engines. More particularly, the present application relates to fuel injection systems for internal combustion engines.

[0002] Fuel injection systems provide fuel to an internal combustion engine. A typical fuel injection system includes a high pressure pump and an injector. The pump provides pressurized fuel from a tank to the injector, and the injector meters the fuel into the air intake or combustion chamber. A typical fuel injector uses a solenoid or piezoelectric system to move a needle, thereby permitting or preventing flow of the pressurized fuel through the fuel injector to an outlet nozzle. Internal combustion engines using fuel injection systems typically have cleaner emissions than carbureted engines; however, in many small engines, and in many parts of the world, carburetors are still widely used due to the cost and complexity of fuel injection systems. Thus, there is a need for an improved fuel injection system. There is a further need for an improved low-cost fuel injection system. There is a further need for a fuel injection system that inhibits the fuel from overheating (e.g., vaporizing, boiling, etc.) before being sprayed.

[0003] US6422836 B1 discloses a reciprocating fluid pump including a drive section and a pump section. The drive section has a pair of coils which may be energized to cause displacement of a reciprocating assembly. Each coil is a reluctance gap arrangement in which a magnetic circuit is interrupted by a gap towards which an armature of the reciprocating assembly is drawn when energizing current is applied to the coil. The reciprocating assembly includes an element which is extended into and retracted from a pump chamber during its reciprocating motion, causing fluid to be drawn into and expelled from the pump chamber. The pump is particularly well suited for use in cyclic pumping applications, such as internal combustion engine fuel injection. Cycle times in such applications may be reduced by appropriate control of the current waveforms applied to the coils.

SUMMARY

[0004] One embodiment relates to a fuel injector including a sleeve having a first end proximate an outlet; a piston slidingly received in the sleeve, the piston having a first end proximate the outlet; a pumping chamber at least partially defined by the sleeve between the first end of the piston and the outlet; and a normally-open inlet valve through which fuel passes to enter the pumping chamber. The inlet valve closes when the piston has sufficient velocity to create sufficient pressure inside the fluid pumping chamber to close the inlet valve or the piston has sufficient acceleration to close the normally-open valve. The inlet valve may further include a valve body biased away from a valve seat by a valve spring, and wherein the inlet valve closes when the piston has sufficient velocity to create sufficient pressure inside the fluid pumping chamber to overcome the force of the inlet valve spring. The fuel injector may include a normally-closed outlet valve coupled to the first end of the sleeve. The inlet valve may be located in the piston. The piston may include a wall coupled to the inlet valve, the wall and the inlet valve at least partially defining a cavity in the piston, wherein fuel passes through the cavity to enter the pumping chamber. The fuel injector may include a magnetic actuation assembly supported by the housing and coupled to the piston, the magnetic actuation assembly configured to translate the piston. The magnetic actuation assembly may include a magnet and a coil.

[0005] An example disclosure relates to a fuel injector including a sleeve having a first end and a second distal the first end; a normally-closed outlet valve coupled to the first end of the sleeve; a piston received in the sleeve and slidable between a first position and a second position, the piston having a first end proximate the outlet valve and a second end distal the first end; a normally-open inlet valve through which fuel passes to enter the pumping chamber, the inlet valve coupled to the first end of the piston; and a pumping chamber at least partially defined by the sleeve between the inlet valve and the outlet valve. Movement of the piston from the second position to the first position forces fluid from the pumping chamber through the outlet valve, and movement of the piston from the first position to the second position draws fluid into the pumping chamber through the inlet valve. Reciprocation of the piston between the first and second positions may cause the fuel injector to act as a positive displacement or impulse pressure pump.

[0006] Another example relates to a control system for a fuel injector. The control system may include a circuit configured to measure the voltage across a coil in the fuel injector corresponding to the velocity of the coil through a magnetic field. The control system may include a circuit configured to measure the voltage across a current sense resistor. The control system may include processing electronics configured to control the velocity and/or position of a piston in the fuel injector, for example, in response to a voltage across the coil and/or a voltage across the current sense resistor. The control system may include processing electronics configured to self-calibrate the control system.

[0007] Another example relates to a fuel injector including a sleeve having a first end proximate an outlet; a piston slidingly received in the sleeve, the piston having a first end proximate the outlet; a pumping chamber at least partially defined by the sleeve between the first end of the piston and the outlet; and a normally-open valve through which fuel passes to enter or exit the pumping chamber. The normally open valve may include an inlet valve coupled to the first end of the piston. The valve may remain open during the beginning of the down stroke. The valve may close when the piston has sufficient velocity to create sufficient pressure inside the fluid pumping chamber or the piston has sufficient acceleration to close the inlet valve. The valve may include a valve body biased away from a valve seat by a valve spring, and the valve may close when the piston has sufficient velocity to create sufficient pressure inside the fluid pumping chamber or the piston has sufficient acceleration relative to the valve body to overcome the force of the valve spring. The outlet may include a normally-closed outlet valve coupled to the first end of the sleeve. The piston may be slidable between a first position and a second position, and movement of the piston from the second position to the first position may force fluid from the pumping chamber through the outlet valve, and movement of the piston from the first position to the second position may draw fluid into the pumping chamber through the valve. The piston may be slidable between a first position and a second position, and reciprocation of the piston between the first and second positions may cause the fuel injector to act as a positive displacement or impulse pressure pump. The piston may include a piston wall coupled to the inlet valve, the wall and the inlet valve at least partially defining a cavity in the piston, wherein fuel passes through the cavity to enter the pumping chamber. The fuel injector may include a magnetic actuation assembly supported by the housing and coupled to the piston, wherein the magnetic actuation assembly may include at least one magnet and a coil and configured to translate the piston. The fuel injector may include an electromagnetic actuation assembly, which may include one or more magnets having a magnetic field, one or more pieces of low reluctance material to focus the magnetic field of the one or more magnets across one or more high reluctance gaps, and a wire coil situated at least partially in the one or more high reluctance gaps such that, when a current is applied to the wire coil, the current interacts with the magnetic field to produce a force. The electromagnetic actuation assembly may further optionally include any or all of the features of the embodiments of the electromagnetic actuation assembly described below. The fuel injector may include a piston assembly, which may include the piston, which may include a piston wall extending from a first end of the piston and at least partially defining a piston cavity and a valve seat located at the first end of the piston; an inlet valve coupled to the piston comprising a poppet, which may include a valve body configured to seal against the valve seat and a valve stem extending from the valve body; a retainer coupled to the valve stem and configured to limit the travel of the poppet relative to the piston; and a valve spring coupled to the piston and biasing the poppet towards one of a normally-open an a normally-closed valve position. The piston assembly may further optionally include any or all of the features of the embodiments of the piston assembly described below. The fuel injector may include an outlet valve assembly, which may include an outlet valve, which may include a valve seat, a valve body, and a spring biasing the valve body against the valve seat such that the outlet valve assembly is normally closed; wherein the valve opens passively under pressure. The outlet valve assembly may further optionally include any or all of the features of the embodiments of the outlet valve assembly described below. The fuel injector may include an electromagnetic coil configured to move the piston and a control system, which may include processing electronics. The processing electronics may be configured to measure a current through the coil in the fuel injector and to determine the at least one of the velocity and the position of the coil through a magnetic field based on the current. The control system may further optionally include any or all of the features of the embodiments of the control system described below. Any or all of the features, limitations, configurations, components, subcomponents, systems, and/or subsystems described above may be used in combination.

[0008] Another example relates to a piston assembly for a fuel injector. The piston assembly includes a piston and a valve. The piston includes a piston wall extending from a first end of the piston and at least partially defining a piston cavity and a valve seat located at the first end of the piston. The valve includes a poppet, which includes a valve body configured to seal against the valve seat and a valve stem extending from the valve body. The piston assembly further includes a retainer coupled to the valve stem and configured to limit the travel of the poppet relative to the piston and a spring coupled to the piston and biasing the poppet towards one of a normally-open an a normally-closed valve position. The spring may bias the piston to a normally open position. The valve may close when the piston has sufficient velocity to create sufficient pressure inside a fluid pumping chamber or when the piston has sufficient acceleration relative to the valve body to overcome the force of the inlet valve spring. The piston may be slidingly received in a sleeve which has at least one pocket of fuel surrounding the sleeve to reduce heat transfer to the piston. The first end of the piston may form the valve seat. During operation, fuel may passes through the piston cavity and may exits the piston through the valve. The retainer may define at least one passageway allowing the fuel to pass therethrough. The spring may be located in the piston cavity and acts against the retainer. Any or all of the features, limitations, configurations, components, subcomponents, systems, and/or subsystems described above may be used in combination.

[0009] Another embodiment relates to an electromagnetic actuation assembly for a fuel injector. The electromagnetic actuation assembly includes one or more magnets having a magnetic field, one or more pieces of low reluctance material to focus the magnetic field of the one or more magnets across one or more high reluctance gaps, and a wire coil situated at least partially in the one or more high reluctance gaps such that, when a current is applied to the wire coil, the current interacts with the magnetic field to produce a force. At least one of the one or more pieces of low reluctance material may be configured such that its proximity to at least one of the one or more magnets and another of the one or more pieces of low reluctance material may be adjusted to calibrate the strength of the magnetic field At least one of the one or more pieces of low reluctance material may include a portion configured to be deflected or deformed to change its proximity to at least one of the one or more magnets and/or another of the one or more pieces of low reluctance material to calibrate the strength of the magnetic field. The portion configured to be deflected or deformed to calibrate the strength of the magnetic field may define a plurality of slots to reduce the force required for deflection or deformation. The portion configured to be deflected or deformed to calibrate the strength of the magnetic field may be a domed portion. A first of the one or more magnets may have a first side and second side, a first of the one or more pieces of low reluctance material may be located to the first side of the magnet, and a second of the one or more pieces of low reluctance material may be located to the second side of the magnet. The electromagnetic actuation assembly may include a third of the one or more pieces of low reluctance material located to the first side of the magnet. The electromagnetic actuation assembly may include a fourth of the one or more pieces of low reluctance material located to the second side of the magnet. The first of the one or more pieces of low reluctance material may define an inner portion of a first of the one or more high reluctance gaps, the second of the one or more pieces of low reluctance material may include a cup shape that may define the outer portion of the first of the one or more high reluctance gaps, and the first of the one or more high reluctance gaps may be annular. Each of the one or more pieces of low reluctance material may be sufficiently thin that it may be formed by stamping. Each of the one or more magnets and one or more pieces of low reluctance material may define holes therethrough, and the ; and the electromagnetic actuation assembly may include a pin extending through the holes in each of the one or more magnets and one or more pieces of low reluctance material. The pin may retain the relative positions of each of the one or more magnets and one or more pieces of low reluctance material with respect to one another. The pin may be a spring pin. The pin may extend in an axial direction, and the magnet may be an axially magnetized permanent magnet. Any or all of the features, limitations, configurations, components, subcomponents, systems, and/or subsystems described above may be used in combination.

[0010] Another embodiment relates to an outlet valve assembly for a fuel injector. The outlet valve assembly includes an outlet valve, which includes a valve seat, a valve body, and a spring biasing the valve body against the valve seat such that the outlet valve assembly is normally closed. The outlet valve opens passively under pressure. The valve body may include a ball located on the downstream side of the valve seat. The spring may be located upstream of the valve seat. The spring may be located downstream of the valve seat. The outlet valve assembly may include an orifice plate located downstream of the valve seat. The orifice plate may include at least one orifice configured to atomize the flow of fuel passing through the orifices. The orifice plate may include an indent configured to align and constrain the spring. The flow rate of the assembly may be calibrated by indenting the orifice plate towards the valve body to increase a preload on the valve spring. The outlet valve assembly may include a second plate located between the valve seat and the orifice plate. The second plate may be configured to increase atomization of the flow of fuel passing through the orifices or to improve control over a spray pattern. The flow rate of the assembly may be calibrated by indenting the orifice plate towards the valve body to reduce a gap between the orifice of plate and the second plate. The outlet valve assembly may include a second plate adjacent an upstream side of the orifice plate and a first plate adjacent an upstream side of the second plate. The first plate and the second plate may cooperate to increase or cause turbulence in a flow of fuel passing through the first and second plates. The first plate may define an aperture having a first diameter, and the second plate may define an aperture having a second diameter greater than the first diameter, and the orifices in the orifice plate may be spaced radially outward of the first diameter. The first plate and the second plate may each defines a plurality of radially extending slots. The first plate may define a plurality of circumferentially extending slots. The outlet valve assembly may include a valve seat body forming the valve seat and may include a bore extending from the valve seat to the plurality of plates, wherein the bore defines the sac. Any or all of the features, limitations, configurations, components, subcomponents, systems, and/or subsystems described above may be used in combination.

[0011] Another embodiment relates to a control system for a fuel injector having a piston and an electromagnetic coil configured to move the piston. The control system includes processing electronics configured to measure a current through the coil in the fuel injector and to determine the at least one of the velocity and the position of the coil through a magnetic field based on the current. The processing electronics may be configured to control the current through the coil in response to the at least one of the velocity and the position of the coil. The processing electronics may measure the current through the coil by measuring a voltage across a current sense resistor. The processing electronics may be configured to determine a start of injection based on the current through the coil. The processing electronics may be configured to determine whether fuel is rapidly vaporizing and in response to a timing of the start of injection. The processing electronics may be configured to control the current through the coil to compensate for the fuel vapor in response to determining that the fuel is rapidly vaporizing. The processing electronics may be configured to determine an end of injection based on the current through the coil. The end of injection may include the piston contacting a bottom of a pumping chamber. The processing electronics may be configured to determine whether there is fuel in the injector based on a timing of the end of injection. The processing electronics may be configured to shut down the fuel injector in response to determining that there is no fuel in the injector. The processing electronics may be configured to determine a baseline elapsed time between a start of injection and an end of injection in response to the current across the coil; after a predetermined number of cycles after determining the baseline elapsed time, determine a second elapsed time between the start of injection and the end of injection in response to the voltage across the current sense resistor; and determine whether the injector flow rate has changed based on the second elapsed time compared to the baseline elapsed time. The processing electronics may be configured to calibrate the control system in response to

determining whether the injector flow rate has changed. Any or all of the features, limitations, configurations, components, subcomponents, systems, and/or subsystems described above may be used in combination, as defined in the appended claims.

[0012] The foregoing is a summary and thus by necessity contains simplifications, generalizations, and omissions of detail. Consequently, those skilled in the art will appreciate that the summary is illustrative only and is not intended to be in any way limiting. Other aspects, inventive features, and advantages of the devices and/or processes described herein, will become apparent in the detailed description set forth herein and taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013]

FIG. 1 is a sectional view of a fuel injector, shown in a first state, according to an exemplary embodiment.

FIG. 2 is a sectional view of the fuel injector of FIG. 1, shown in a second state, according to an exemplary embodiment.

FIG. 3 is a sectional view of the fuel injector of FIG. 1, shown in a third state, according to an exemplary embodiment.

FIG. 4 is a perspective, cutaway view of the magnetic structure and moving components of the fuel injector of FIG. 1.

FIG. 5 is a sectional view of a portion of the fuel injector of FIG. 1, shown in a first state, according to an exemplary embodiment.

FIG. 6 is an exploded, perspective view of an outlet valve assembly of the fuel injector of FIG. 1.

FIG. 7 is a sectional view of the outlet valve assembly of the fuel injector of FIG. 6.

FIG. 8 is an exploded, perspective view of an outlet valve assembly of the fuel injector of FIG. 1, according to another embodiment.

FIG. 9 is a sectional view of the outlet valve assembly of the fuel injector of FIG. 8.

FIG. 10 is a perspective, one-quarter cutaway view of a fuel injector, shown in a first state, according to another embodiment.

FIG. 11 is a perspective, one-half cutaway view of the fuel injector of FIG. 10, shown according to an exemplary embodiment.

FIG. 12 is a sectional view along line A-A of FIG. 11, shown according to an exemplary embodiment.

FIG. 13 is an exploded, perspective view of an outlet valve assembly of the fuel injector of FIG. 10.

FIG. 14 is a sectional view of the outlet valve assembly of the fuel injector of FIG. 13.

FIG. 15 is an exploded, perspective view of an outlet valve assembly, shown according to another embodiment.

FIG. 16 is a sectional view of the outlet valve assembly of the fuel injector of FIG. 15.

FIG. 17 is a general schematic block diagram of the processing electronics of the aviation display control system of FIG. 4, according to an exemplary embodiment.

FIG. 18 is a schematic diagram of a circuit used to sense and control the fuel injector of FIG. 1, shown according to an exemplary embodiment.

FIG. 19 is a graph of voltage across the coil of the fuel injector of FIG. 1 or 10, shown according to an exemplary embodiment.

FIG. 20 is a graph of voltage across a current sense resistor of the circuit of FIG. 18, shown according to an exemplary embodiment.

FIGS. 21-22 are a schematic flow chart of a process of controlling a fuel injection system.

DETAILED DESCRIPTION

[0014] Referring generally to the FIGURES, a fuel injection system, and components thereof, are shown according to an exemplary embodiment. The fuel injection system is shown to include a fuel injector and a control circuit. The injector includes a reciprocating piston, an inlet valve, an outlet valve, and a fluid pumping chamber. The injector further includes a coil actuator and a magnetic field, the interaction of which produces an electromagnetic force which drives the piston. Motion of the reciprocating piston in a direction that reduces the volume of the fluid pumping chamber forces fuel out of the injector. The inlet valve is normally open and closes when the piston moves with sufficient speed to generate sufficient pressure inside the fluid pumping chamber. The inlet valve may also close when the acceleration of the piston relative to the inlet valve body is sufficient to overcome the force of the inlet valve spring. Motion of the piston within the injector forces the fuel out through the orifice under pressure, thus negating the need for a separate high pressure fuel pump and pressure regulator, as required by conventional fuel injection systems, thus reducing the number of parts and components which are typically costly to produce. The injector may deliver fuel to the intake or directly into the combustion chamber of an internal combustion engine. While the fuel injection system is described with respect to fuel and internal combustion engines, the system may be used with other fluids in other applications. For example, the injector may be used to spray or inject other liquids, for example, water, beverage, paint, ink, dye, lubricant, scented oil, etc.

[0015] An exemplary circuit is provided for sensing and controlling the injector. Methods of sensing may use the circuit, or portions thereof, to directly determine the velocity of the piston and to indirectly determine the position of the piston. Methods of control may use the circuit, or portions thereof, to meter the amount of fuel injected for each pumping stroke of the piston. The sensing and controlling may be combined to form a closed-loop control system of the injector to precisely meter the amount of fuel being injected. In other embodiments, the injector may be operated in an open-loop system.

[0016] Before discussing further details of the fuel injection system and/or the components thereof, it should be noted that references to "top," "bottom," "upward," "downward," "inner," "outer," "right," and "left" in this description are merely used to identify the various elements as they are oriented in the FIGURES. These terms are not meant to limit the element which they describe, as the various elements may be oriented differently in various applications.

[0017] It should further be noted that for purposes of this disclosure, the term "coupled" means the joining of two members directly or indirectly to one another. Such joining may be stationary in nature or moveable in nature and/or such joining may allow for the flow of fluids, electricity, electrical signals, or other types of signals or communication between the two members. Such joining may be achieved with the two members or the two members and any additional intermediate members being integrally formed as a single unitary body with one another or with the two members or the two members and any additional intermediate members being attached to one another. Such joining may be permanent in nature or alternatively may be removable or releasable in nature.

[0018] Referring to FIGS. 1-9, an injector 10 (e.g., sprayer, fuel injector, positive displacement pump, etc.) is shown, according to an exemplary embodiment. The injector 10 includes a housing 2, shown to include a first or upper portion, shown as end cap 4, and a second portion, shown as lower portion 6, coupled to the end cap 4. The end cap 4 is shown to include a fuel inlet 31, a vapor outlet 29, and an electrical plug or connector 24. One or more fuel filters (not shown) may be installed on the fuel inlet 31 and/or the vapor outlet 29. The end cap 4 defines a main cavity 30 and receives and supports a magnetic actuation assembly (e.g., an electromagnetic actuation assembly). The magnetic actuation assembly includes one or more magnets, shown as a magnet 11. The magnetic actuation assembly further includes one or more pieces of low reluctance material configured to focus the magnetic field of the one or more magnets across one or more high reluctance gaps. According to the exemplary embodiment shown, the one or more pieces of low reluctance material include, a pole piece 12 and a plate 13 (e.g., front plate, bottom plate, etc.). A coil 15 (e.g., a wire coil, etc.) is located at least partially in the one or more high reluctance gaps such that, when a current is applied to the coil 15, the current interacts with the magnetic field to produce a force. The lower portion 6 defines a cavity configured to receive a piston 17 therein. The piston 17 is coupled to the magnetic actuation assembly by a cage 16, which transfers motion and forces therebetween. The magnet 11, pole piece 12, plate 13, coil 15, cage 16, former 38 and piston 17 are shown to be axially aligned along an axis 8 (e.g., longitudinal axis). According to various embodiments, the one or more of the components of the magnetic actuation assembly, the cage 16, the former 38, and the piston 17 are centered about the axis 8. While various components and elements are shown and described as being in either the end cap 4 or the lower portion 6, it is contemplated that, in various embodiments (e.g., injector 610, described in more detail below), a given component or element may be in either or both portions of the housing, or that the injector 10 may include a unitary housing.

[0019] The magnet 11 may be an axially magnetized permanent magnet coupled between (e.g., sandwiched between, interconnecting, etc.) the pole piece 12 and the plate 13, which are both made of a material with high magnetic permeability such as iron, low carbon steel, etc. According to other embodiments, other configurations found in "voice-coil" type actuators can be used to produce the same function, for example, a radially magnetized permanent magnet concentric with, and on the inside and/or outside of the coil 15. The pole piece 12 and the plate 13 define an annular gap 14 radially therebetween. The coil 15 is situated in the gap 14 with sufficient inward and outward radial clearance from the pole piece

12 and the plate 13, respectively to permit axial movement of the coil 15. The coil 15 is coupled to the cage 16 via the former 38, and the cage 16 is coupled to the piston 17. The coil 15 is wound from an electrically conductive material such as copper or aluminum with insulation. The cage 16 has at least one slot which allows fuel to pass therethrough and which minimizes the weight and drag of the cage 16.

[0020] According to the exemplary embodiment shown, magnetic actuation assembly comprises a moving coil type actuator (e.g., a "voice-coil" type actuator). The moving coil type actuator advantageously provides low inductance and hysteresis, which is well-suited for high frequency operation. Furthermore, the force acting on the coil 15 increases linearly with the current flowing therethrough and the force remains nearly constant throughout its entire stroke. These characteristics facilitate control of the actuator. Furthermore, the moving type actuator generates a large back EMF voltage proportional to its speed as it moves through the magnetic gap 14 between the pole piece 12 and plate 13. This back EMF voltage can be exploited to sense the velocity and derive the position of the coil 15. As described in an exemplary embodiment below, this information can be used in a closed-loop feedback control scheme to precisely meter the amount of fluid being injected or sprayed even in the presence of disturbances such as the presence of vapor bubbles and variations in supply voltage. According to other embodiments, a solenoid type actuator may be used. The position of the armature in a solenoid type actuator changes the solenoid coil's reactance, which affects the current through the solenoid coil and can be used to detect the velocity and position of the armature or plunger.

[0021] According to the embodiment shown, the piston 17 includes a substantially cylindrical wall having a first or top end, proximate the plate 13, and a second or bottom end, distal the plate 13. The piston wall defines a longitudinal piston cavity through which fluid passes during the piston pumping cycle, i.e., the injection cycle. The bottom end of the piston 17 is shown to include a piston end face 39 and an inlet valve seat 33 formed in the bottom end of the piston 17. The piston 17 is received in sleeve 21, which in turn is received in the lower portion 6 of the housing 2. The sleeve 21 is configured to permit axial translation or sliding of the piston 17 therein. The sleeve 21 may be a formed as a part of the housing 2 (e.g., as a bore formed or machined therein), or the sleeve 21 may be formed separately from the housing 2 and subsequently coupled thereto. The sleeve 21 further includes a ledge or step 20, and the cage 16 also includes a ledge or step 19. A main spring 18 is located between the step 19 on the cage 16 and the step 20 on the sleeve 21, and biases the cage 16 towards the plate 13. According to another embodiment, the main spring 18 can bias the cage 16 towards the outlet valve retainer 102. The upstroke or suction stroke of the piston 17 is initiated completely by the force of the coil 15; whereas, the down stroke of the piston 17 can be powered by the main spring 18 alone or with the help of the coil force in the reverse direction. This embodiment may allow a more precise control of the stroke of the piston 17.

[0022] Fresh fuel enters into the main cavity 30 (e.g., fuel chamber) via the fuel inlet 31. According to one embodiment, liquid fuel enters the piston cavity from the main cavity 30 via one or more holes 25 through the wall of the piston 17. According to another embodiment, the liquid fuel may pass through the cage 16 and enter the piston cavity through the top end of the piston 17 as piston 17 moves away from the plate 13 (see e.g., FIGS. 2 and 3).

[0023] The fuel inlet 31 is located relatively low on the injector 10 relative to the main cavity 30 and the vapor outlet 29. Any vapor in the injector 10 rises to the top of the injector 10 and out of the vapor outlet 29 due to buoyancy. Fuel vapor present in the injector 10 may come from the fuel supply (e.g., through fuel inlet 31) and/or may be generated inside the injector 10 due to a reduction in pressure and/or an increase in temperature. As shown, the fuel inlet 31 is substantially horizontal; however, the fuel inlet 31 may extend at downward angle from the end cap 4 to inhibit fuel vapor from travelling upstream through the fuel inlet 31. A series of holes, opening, orifices, etc., may form a low resistance path or passageway extending through the pole piece 12, the magnet 11, and the plate 13, to allow fuel vapor present in the fuel injector to escape through the vapor outlet 29 as part of the end cap 4. For example, according to one embodiment, the holes may be centrally aligned along longitudinal axis 8, shown as passageway 28. According to another embodiment, the holes may be offset from the axis 8, shown as passageway 27. According to another embodiment, the vapor passageway may include spacing between the pole piece 12 and the housing 2. Such venting of the fuel vapors helps provide reliable operation of the fuel injector during hot operating conditions.

[0024] Referring specifically to FIG. 4, an inlet valve 50 is located at the bottom end of the piston 17, according to an exemplary embodiment. As shown, the inlet valve 50 is a poppet valve that includes an inlet valve body 32 coupled to an inlet valve stem 34, an inlet valve retainer 35, and an inlet valve spring 36. The inlet valve body 32 seals against the inlet valve seat 33 at the bottom end of the piston 17. The inlet valve body 32 is shown to have a semi-spherical shape while the inlet valve seat 33 is shown to have a conical shape to provide self-alignment of the inlet valve body 32 to the inlet valve seat 33, which improves sealing therebetween. The rounded lip on the inlet valve body 32 reduces the pressure drop of the fuel flowing into the fluid pumping chamber 40. According to the embodiment shown, the inlet valve body 32 is coupled to the inlet valve stem 34 via an interference fit. The inlet valve stem 34 is received by and axially translates (e.g., slides) within an aperture (e.g., opening, hole, central hole, etc.) through the inlet valve retainer 35. The inlet valve retainer 35 is shown to include at least one slot which allows fuel to pass therethrough and is coupled to the piston 17, for example, via an interference fit or an adhesive. As shown, the inlet valve retainer 35 is in a cup shape which can be formed out of a thin sheet by relatively inexpensive methods (e.g., stamping, etc.) and can provide interference fit with the piston without excessive force which can cause deformation thereof. According to another embodiment, the inlet valve body 32 may be unitarily or integrally formed with the inlet valve stem 34, which in turn is coupled to a flange 37 (e.g., projection, stub, etc.) via an interference fit.

[0025] According to the exemplary embodiment shown, the inlet valve body 32 is biased away from the inlet valve seat 33 by the inlet valve spring 36 so that it is normally open, i.e., normally allows fuel to enter into the fluid pumping chamber 40 from inside the piston cavity. The flange 37 on an end of the inlet valve stem 34 distal the inlet valve body 32 limits the travel of the inlet valve body 32 in the open position. The fluid pumping chamber 40 is substantially defined on top by the piston end face 39 and inlet valve body 32, on the bottom by the top face 101 of an outlet valve retainer 102 and an outlet valve seat body 103, and on the sides by the inside wall of the sleeve 21.

[0026] The normally open inlet valve 50 allows fuel to enter the fluid pumping chamber 40 by gravity alone, which reduces the priming requirements particularly when the fluid pumping chamber 40 is full of fuel vapor or when there is no fuel in the injector 10 at all. The normally open inlet valve 50 combined with its large flow area also reduces the pressure drop during the upstroke of the piston 17, which reduces the formation of fuel vapors. Furthermore, having the inlet valve 50 open at the start of an injection cycle allows the piston 17 to gain velocity without significant resistance. Once the inlet valve 50 closes, the piston 17 will have gained enough velocity to generate a high pressure inside the fluid pumping chamber 40, which increases the amount of initial fuel atomization through the orifice plate 112 of the outlet. Further, the increased velocity of the piston 17 may create sufficient pressure in the fluid pumping chamber 40 to collapse or condense fuel vapor bubbles therein. Upon closing of the inlet valve 50, the pressure in the fluid pumping chamber 40 increases substantially. This large pressure rapidly decelerates the piston 17, partially also due to the low mass of the moving components. This substantial reduction in velocity can be observed by monitoring the voltage across a current sense resistor (which corresponds to the current through the coil 15) to mark the beginning of an injection event. According to another embodiment, the inlet valve 50 can be located elsewhere other than on the piston 17 such as on the sleeve 21, while still in fluid communication with the fluid pumping chamber 40. According to another embodiment, the inlet valve 50 may also be used with another check valve such that one valve is responsible for introducing fluid into the fluid pumping chamber 40, while the other valve is used to expel vapor.

[0027] Another advantage of the normally open inlet valve 50 is that it allows fuel vapor in the fluid pumping chamber 40 to pass through the inlet valve 50 due to the orientation of the injector 10 and the buoyancy of the fuel vapor relative to the liquid fuel. The presence of fuel vapor bubbles in the fluid pumping chamber 40 could potentially cause a positive displacement type pump to meter the incorrect amount of fuel. This is due to the fact that the presence of bubbles will change the bulk density of the fuel being metered so that the same volume of fuel being injected will not correspond to the same mass. The chances of fuel vapor bubbles being generated or brought into the fluid pumping chamber is high in particular when the fuel injector is hot and during the upstroke of the piston 17 in which the flow of fuel past the restriction of the inlet valve 50 causes the fuel to decrease in pressure. According to embodiments described in more detail below, the injector 10 provides an initial low pressure portion of the stroke in which the inlet valve 50 does not close and any vapor bubbles present in the fluid pumping chamber 40 exits through the inlet valve 50 and/or may be condensed into liquid form. It is contemplated that in other embodiments, a normally open valve through which fuel does not enter the fluid pumping chamber may be fluidly coupled to the fluid pumping chamber 40 to allow vapor to exit the fluid pumping chamber 40 until a sufficient pressure is created in the fluid pumping chamber 40 to close the valve. Such a normally open valve may be fluidly coupled to the vapor outlet 29.

[0028] Referring to FIG. 3, the piston 17 is limited in travel in the downward direction by the outlet valve retainer 102. According to one embodiment, the end face 39 contacts (e.g., touches, impacts, kisses, etc.) a top face 101 of the outlet valve retainer 102. The end face 39 contacting the top face 101 may include embodiments in which the end face 39 is spaced apart from top face 101 by a minimal amount of residual fluid. The residual fluid may act as shock absorber between the end face 39 and the top face 101. According to an exemplary embodiment, the fluid in the fluid pumping chamber 40 reduces or limits the speed of the piston 17 as it approaches the outlet valve retainer 102, thereby absorbing some of the shock of contact as the last remnants of fluid are pushed out of the fluid pumping chamber 40. According to another embodiment, a disk spring may be placed on top of the outlet valve retainer 102 to reduce the impact force of the piston 17. According to other embodiments, the piston 17 does not contact the outlet valve retainer 102. However, during the high pressure portion of the stroke, the fuel inside the fluid pumping chamber 40 has an elevated temperature due to the increase in pressure. After the high pressure portion of the stroke, the hot fuel inside the high compression chamber can flash (e.g., evaporate, boil, etc.) into vapor because its pressure falls to near atmospheric levels. The small volume between the piston 17 and the outlet valve retainer 102 when the piston 17 is at the bottom position (i.e., at the bottom end of the stroke) limits the amount of vapor that is generated.

That is, reducing the amount of fuel remaining in the fluid pumping chamber 40 may reduce the amount of fuel vapor generated during the upstroke of the piston 17. Further, as shown and described, the inlet and outlet valve configurations provide the injector 10 with a large compression ratio (the ratio of the maximum volume of the fluid pumping chamber 40 when the piston 17 is at its top position to the minimum volume of the fluid pumping chamber 40 when the piston 17 is at its bottom position), which increases the self-priming ability of the injector 10. Other outward opening inlet valve and outlet valve retainer embodiments may be used in which the compression ratio is also high. For example, the bottom face of the valve body 32 can be semi-spherical instead of flat, and the upper face of the outlet valve retainer will have a corresponding shape as to minimize the volume therebetween when the piston has reached the bottom of its travel. In other embodiments, the sphere-to-cone sealing surface between the valve body 32 and valve seat 33 may be substituted for other sealing geometries, for example, face-to-face.

[0029] Referring to FIGS. 6 and 7, an outlet valve assembly 100 is located in the bottom of the lower portion 6 of the housing 2, according to an exemplary embodiment. The outlet valve includes the outlet valve retainer 102, the outlet valve seat body 103, an outlet valve body 105 (e.g., ball, check, etc.), and an outlet valve spring 106. The outlet valve retainer 102 supports the outlet valve seat body 103 which has an outlet valve seat 104. The outlet valve body 105 is biased towards the outlet valve seat 104 by the outlet valve spring 106. According to the embodiment shown, the outlet valve body 105 is a polished sphere and the outlet valve seat 104 is a polished cone, thereby ensuring self-alignment and a good seal. The outlet valve spring 106 is sandwiched between the outlet valve body 105 and a first plate, shown as a turbulence generating plate 107. The turbulence generating plate 107 has at least one slot 108, shown to extend in an at least partially circumferential arc. The one or more slots 108 allow fuel to pass therethrough to a turbulence gap 109 defined by a second plate, shown as an outlet washer 110 (e.g., disc, plate, etc.) and out of the fuel injector through one or more orifices 111 passing through a third plate, shown as an orifice plate 112. A sealing washer 113 (e.g., ring, disc, plate, etc.) seals the orifice plate 112 against the lower portion 6 of the housing 2. A filter 114 may be used to prevent debris from entering the outlet valve. The outlet valve assembly 100 as shown, in particular the arrangement of the turbulence generating plate 107, the outlet washer 110, and the orifice plate 112 is able to achieve a high turbulence in the fuel flow which increases the amount of fuel atomization. The above three components can be manufactured out of sheet metal by inexpensive methods.

[0030] Referring to FIGS. 8 and 9, an outlet valve assembly 500 is shown according to another exemplary embodiment. The outlet valve assembly 500 is located in the bottom of the lower portion 6 of the housing 2. The volume of fuel between the outlet valve seat 104, 504 and the orifices 111, 511 is commonly referred to as the "sac". During hot operating conditions, this volume of fuel has a tendency to drip into the engine intake and/or engine cylinder, which may affect fuel metering and may deposit liquid fuel (e.g., non-atomized fuel) into the engine intake and/or engine cylinder. The embodiment of the outlet valve shown in FIGS. 8 and 9 reduces the "sac" volume, thereby reducing leakage of fuel into the engine intake and/or engine cylinder. The outlet valve includes an outlet valve retainer 502, an outlet valve seat body 503, an outlet valve body 505 (e.g., ball, check, etc.), and an outlet valve spring 506. The outlet valve retainer 502 supports the outlet valve seat body 503 which has an outlet valve seat 504. The outlet valve body 505 is biased towards the outlet valve seat 504 by the outlet valve spring 506. According to the embodiment shown, the outlet valve body 505 is a polished sphere and the outlet valve seat 504 is a polished cone, thereby ensuring self-alignment and a good seal. The turbulence generating plate 507 is located below the outlet valve seat body 503 and has at least one radially oriented slot 508. A sac sealing film 510, preferably made of an easily deformable, resilient material or a soft flexible material, is located below the turbulence generating plate 507 and also has at least one radially oriented slot 509. As shown, the plurality of radially oriented slots 509 on the sac sealing film 510 overlap (i.e., align with) the plurality of radially oriented slots 508 on the turbulence generating plate 507. The sac sealing film 510 is also located between the outlet valve spring 506 and the outlet valve body 505. An orifice plate 512 is located below the sac sealing film 510 and has one or more orifices 511 aligned with the slots 508, 509 on the turbulence generating plate 507 and the sac sealing film 510. The center of the orifice plate 512 is a formed in the shape of a cup 515 to receive the outlet valve spring 506. The cavity of the cup 515 can be vented to the outside of the cup 515 by the opening 516 (e.g., orifice, hole, vent, etc., best seen in FIG. 9) and is sealed against the sac volume by the sac sealing film 510. According to another embodiment, the cup 515 that receives the outlet valve spring 506 may be part of a member that is separate from the orifice plate 512. A sealing washer 513 (e.g., ring, disc, plate, etc.) seals the orifice plate 512 against the lower portion 6 of the housing 2. A filter 514 may be used to prevent debris from entering the outlet valve.

[0031] Referring to FIGS. 10-16, an injector 610 is shown, according to an exemplary embodiment. The injector 610 is generally similar to the injector 10. For example, as seen in FIG. 10, the injector 610 includes a housing 602, shown to include a first or upper portion, shown as end cap 604, and a second portion, shown as lower portion 606, coupled to the end cap 604. The injector 610 further includes a magnetic actuation assembly, which includes one or more magnets 611, one or more pieces of low reluctance material, and a coil 615. According to the exemplary embodiment, the one or more pieces of low reluctance material include one or more pole pieces 612 (shown as first and second pole pieces 612a, 612b) and one or more plates 613 (shown as first and second plates 613a, 613b). The injector 610 is further shown to include a piston 617 coupled to the magnetic actuation assembly by a cage 616. The magnet 611, the pole pieces 612, the plates 613, the coil 615, the cage 616, and the piston 617 are shown to be axially aligned along an axis 608. Notable differences between the injector 610 and the injector 10 will be described. It should be noted that according to various other embodiments, however, various components, assemblies, subassemblies, systems, and/or subsystems, described with respect to the injector 10 and/or with respect to the injector 610 may be used in any suitable combination.

[0032] Further referring to FIG. 11, the lower portion 606 defines a main cavity 630 and receives and supports the magnetic actuation assembly. The lower portion 606 further defines a cavity configured to receive the piston 617 therein. An electrical plug or connector 624 is shown operably coupled to the lower portion 606. The lower portion 606 and the end cap 604 may be formed of any suitable material. According to an exemplary embodiment, the lower portion 606 and the end cap 604 may be injection molded, for example, from glass-filled nylon. The end cap 604 is shown to include a fuel inlet 631 and a vapor outlet 629. Locating the fuel inlet 631 and the vapor outlet 629 on the end cap 604 facilitates manufacture, assembly, and packaging of the injector 610. For example, locating the fuel inlet 631 and the vapor outlet 629 on the end cap 604 facilitates injection molding of the parts, and facilitates routing of the inlet and outlet lines that are coupled to the fuel inlet 631 and the vapor outlet 629, respectively. Further, the base 603 of the end cap 604, from which the fuel inlet 631 and the vapor outlet 629 extend, may be coupled (e.g., heat welded, ultrasonically welded, etc.) to the sidewall 605 of the lower portion 606 to form a robust fluid seal.

[0033] In a gravity fed system (e.g., a pumpless system), the vapor outlet 629 allows fuel vapor to rise buoyantly out of the housing 602. In a pressurized fuel injection system, for example a system having a lifter pump in the fuel tank, the vapor outlet 629 may serve as an outlet port for returning excess fuel and vapor to the fuel tank. In an upright position, as shown in FIGS. 10-12, vapor rises upwards through vapor outlet 629. In other installations, the injector 610 may be packaged at other orientations so long as the vapor outlet 629 is above the central axis 608 so that vapor may rise out of the housing 602. For example, referring briefly to FIG. 12, the injector 610 may be installed in a position between that shown and a position rotated 90 degrees counterclockwise from that shown.

[0034] Referring to FIG. 12, the injector 610 includes one or more pole pieces 612 and one or more plates 613 to guide the magnetic field of magnet 611. As shown, the first pole piece 612a, the second pole piece 612b, the first plate 613a, and the second plate 613b are formed from thin plates, which facilitates stamping of the pole pieces 612 and the plates 613. The magnet 611, the pole pieces 612, and the plates 613 are fixed together by a pin 660 (e.g., a spring pin, etc.) that is pressed through coaxial holes in each of the magnet 611, pole pieces 612, and plates 613. From a practical perspective, the magnet 611 holds the stack of pole pieces 612 and plates 613 together by magnetic force;, the pin 660 ensures that the stack remains radially or coaxially aligned as well as providing axial holding force. According the embodiment shown, the pin 660 and the stack are coaxially aligned with the axis 608.

[0035] A further advantage of using multiple pole pieces 612 and/or multiple plates 613 is that by pressing or coupling together the pole pieces 612 and/or the plates 613 more tightly to reduce the air gaps between them, a stronger magnetic field is created. Preferably, the pole pieces are magnetically saturated previous to calibration such that closing the air gap between the poles reduces their reluctance. Accordingly, the strength of the magnetic field, and therefore the resulting actuation force of the piston 617, can be calibrated. For example, after an initial flow test of the injector 610, the pole pieces 612 and/or the plates 613 may be pressed together a predetermined amount (e.g., distance) to calibrate the injector 610 such that it has desired or standard spray properties. To facilitate calibration, referring to FIGS. 11 and 12, the second pole piece 612b may include a first or outer region 662 and a second or inner region 664. As shown, the inner region 664 forms a dome (e.g., cone, frustum, etc.) and is spaced apart from the outer region 662 by a plurality of slots 666. The slots 666 enable the deformation of the second pole piece 612b without requiring excessive force. During calibration, the inner region 664 is pressed down (e.g., deflected, deformed, etc.) to reduce the air gap between pole pieces 612a and 612b and increase the magnetic strength.

[0036] In one embodiment, the end cap 604 does not contact the inner region 664 and there are one or more holes (not shown) in the end cap 604 which allow the pressing of the second pole piece 612b after the end cap has already been fastened. The air gap is set after calibration due to the permanent deformation of the second pole piece 612a and the friction or press fit between the pin 660 and an inner surface 668 of the second pole piece 612b. The hole or holes are capped after calibration has been completed. In another embodiment, the end cap 604 contacts the top of the inner region 664 and the calibration consists of varying the axial position of the end cap 604 followed by securing it to the lower portion 606 after calibration has been completed. The magnetic structure and air gap are fixed by the friction between the first pole piece 612a and the lower portion and the preload force between the contact of the second pole piece 612a and the end cap 604.

[0037] According to the exemplary embodiment shown, the cage 616 is overmolded onto the coil 615. For example, the cage 616 may be formed of injection-molded, glass-filled nylon. Overmolding the cage 616 onto the coil 615 provides structural strength to the coil, protects the coil from fuel, and protects the connection of the electrically conductive leads 622 to the coil 615, thereby increasing reliability and durability of the injector 610. Further, the overmolding process eliminates the need to adhesively mount the coil 615 to the cage 616, thereby increasing reliability and facilitating manufacture. Additionally, the vent holes 625 may be formed in the cage 616 is part of the injection molding process, further simplifying manufacture of the injector 610.

[0038] Referring to FIG. 12 towards the bottom or outlet end of the piston 617, an inlet valve 650 is shown according to an exemplary embodiment. The inlet valve 650 is shown to include an inlet valve stem 634 extending axially from the inlet valve body 632. The inlet valve body 632 may seal against the inlet valve seat 633 formed at the bottom end of the piston 617. An inlet valve retainer 635 is pressed onto the inlet valve stem 634. According to an exemplary embodiment, the inlet valve stem 634 may be knurled, and the inner portion 672 of the inlet valve retainer 635 may be formed of plastic which bites into the knurling to prevent slippage of the inlet valve retainer 635 relative to the inlet valve stem 634. A plurality of passageways 674 permit fuel to pass through the inlet valve retainer 635. A metal sleeve 676 pressed around the inner portion 672 facilitate sliding of the inlet valve retainer 635 relative to the piston 617. An inlet valve spring 636 pushes the inlet valve retainer 635 away from the cage 616. As shown in FIG. 12, the inlet valve 650 is in a normally open position in which the inlet valve retainer 635 rests against the ledge 678 on an inner surface of the piston 617, and the inlet valve body 632 spaced apart from the inlet valve seat 633. When the inlet valve 650 is in a closed position, the inlet valve body 632 seals against the inlet valve seat 633, and the inlet valve retainer 635 spaced apart from the ledge 678. Accordingly, the ledge 678 and the inlet valve seat 633 limit the movement of (e.g., trap, retain, etc.) the inlet valve 650 relative to the piston 617.

[0039] Piston 617 is shown to be located in a sleeve 621. A sidewall of the sleeve 621 is spaced apart from the lower portion 606 of the housing 602 to form a cavity 680. During operation, cavity 680 fills with fuel, which limits heat transfer from the housing 602 to the piston 617. For example, as a unit of fuel in the cavity 680 absorbs heat, it becomes more buoyant and rises out of the cavity 680 to be replaced by a cooler unit of the fuel. Further, during normal operation, the maximum temperature of the fuel in the cavity 680 is the boiling temperature of the fuel. At this point, the unit of fuel must absorb its heat of vaporization before the temperature can rise further. By limiting the temperature surrounding the sleeve 621 and the piston 617 to less than the boiling point of the fuel, boiling or bubbling of the fuel in the piston 617 is inhibited. According to an exemplary embodiment, fuel passes through the piston 617 at a rate or velocity that prevents the fuel from absorbing heat fast enough to cause the fuel to boil when the temperature in the cavity 680 is limited to the boiling temperature of the fuel.

[0040] Referring to the bottom of FIG. 12, a valve keeper 690 retains the outlet valve assembly in the housing 602. The valve keeper 690 may be located in a bore 692 of the lower portion 606 of the housing 602. In one embodiment, during assembly, the depth that the valve keeper 690 is inserted or pressed into the bore 692 may be selected to compensate for the tolerance stackup of other components in the injector 610. For example, according to the exemplary embodiment shown, the valve keeper 690 is connected to the outlet valve assembly 700, which is connected to the sleeve 621, which is connected to the main spring 618, which is connected to the cage 616, which via the coil 615 is held relative to the magnet 611, which is connected to the first pole piece 612a, which (as best seen in FIG. 10) is supported by a ledge 607 in the sidewall 605 of the lower portion 606 of the housing 602. Accordingly, moving the valve keeper 690 relative to the lower portion 606 may move the aforementioned components relative to one another, particularly compressing the main spring 618. Compressing or pre-loading the main spring 618 calibrates the main spring 618 to affect the motion of the piston 617, which in turn affects the spray characteristics of the injector 610. For example, compressing the main spring 618 changes the x position of the main spring 618, therefore, changing the force applied by the main spring 618 according to the equation $F=kx$. The calibration of the main spring 618 may be further affected if the spring constant k is a function of x. Once the desired position of the valve keeper 690 is achieved, the valve keeper 690 may then be, for example, heat welded or ultrasonically welded to the lower portion 606 to fix the valve keeper relative thereto and to form a seal therebetween. According to another embodiment, the position of the bore is fixed by a ledge 725, best seen in Fig. 13. According to the exemplary embodiment shown, when the end cap 604 and valve keep 690 are sealed to the lower portion 606, the housing 602 of the injector 610 is completely sealed, save for the fuel inlet 631, the vapor outlet 629, and the outlet valve assembly 700, thereby inhibiting leakage of fuel from the injector 610.

[0041] Referring to figures 13 and 14, an outlet valve assembly 700 is shown according to an exemplary embodiment. The outlet valve assembly 700 includes an outlet valve retainer 702 having a central bore 718 configured to receive an outlet valve seat body 703. According to an exemplary embodiment, the outlet valve seat body 703 is formed of a hard, durable material such as metal (e.g., stainless steel, brass, etc.) and has at least one barb 720 formed on an outer surface thereof. The barb 720 engages the softer material (e.g., plastic, etc.) of the outlet valve retainer 702 to both retain and seal the outlet valve seat body 703 in the central bore of the outlet valve retainer 702. As shown, a sealing member 722 (e.g., O-ring, gasket, etc.) helps to seal between the outlet valve seat retainer 702 and the lower portion 606 of the housing 602. According to another embodiment, the outlet valve retainer 702 maybe formed with, instead of or in addition to the sealing member 722, one or more barbs to seal against the lower portion 606 of the housing 602.

[0042] The outlet valve seat body 703 includes an outlet valve seat 704. An outlet valve body 705 (e.g., ball, check, etc.) is biased towards the outlet valve seat 704 by an outlet valve spring 706. According the embodiment shown, the outlet valve body 705 is a polished sphere, and the outlet valve seat 704 has a narrow conical or spherical seat formed at a right angle ledge having a high degree of surface finish, roundness, and flatness.

[0043] The outlet valve spring 706 is compressed between the outlet valve body 705 and the orifice plate 712. The orifice plate 712 includes one or more orifices 711 passing through the orifice plate 712. A washer plate 710 defining a relatively large aperture 709 (e.g., hole, passage, aperture having a first diameter, etc.) sits atop the orifice plate 712, between the orifice plate 712 and the outlet valve retainer 702. A turbulence generating plate 707 defining a relatively small aperture 708 (e.g., defining an aperture having a second diameter that is lesser than the first diameter, etc.) sits atop the washer plate 710, between the washer plate 710 and the outlet valve retainer 702. As shown, the outlet valve spring 706 passes through the relatively small aperture 708 and the relatively large aperture 709 to press against the orifice plate 712. Each of the turbulence generating plate 707, the washer plate 710, and the orifice plate 712 are shown to be formed (e.g., stamped) with a peripheral flange 724 that facilitates nesting of the plates 707, 710, and 712 and (as best see in FIG. 14) facilitates a press fit between the plates 707, 710, 712 and the lower portion 606 of the housing 602. The orifice plate is shown to have a central indent which helps to align and constrain the outlet valve spring during operation. The plates 707, 710, 712 may also have radially oriented slots on the peripheral flange 724 that allows the alignment of the plates to the lower portion 606 of the housing 602 while reducing stresses in the plates after assembly that may reduce their flatness.

[0044] During operation, fuel flows around the outlet valve body 705, through the sac 730 the turbulence generating plate 707. Fuel passes through the relatively small aperture 708 and spreads turbulently outward into the relatively large aperture 709 before passing through the orifices 711 and out of the outlet valve 700. As best seen in FIG. 14, the orifices 711 are spaced radially outwardly from the relatively small aperture 708, thereby requiring the fuel to spread outwardly in the relatively large aperture 709, which creates turbulent flow. The outlet valve assembly 700 has several advantages. Firstly, a spherical valve body allows the use of bearing balls, which are fabricated with high roundness, dimensional, and surface finish requirements and are low in cost. A spherical outlet valve body 705 also allows the self-centering of the outlet valve spring 706. Using an orifice plate downstream of the valve body allows the fuel to be well atomized while protecting the sealing members from fouling and other potentially adverse effects caused by direct exposure to an engine intake manifold. According to other embodiments, various plates can be added or exchanged between the outlet valve body 705 and the orifice plate 712 in order to improve atomization, change the spray pattern, and/or change the flow rate of the fuel without significant changes to the other components of the injector or to the overall assembly process. The flow rate through the outlet valve assembly 700 may be calibrated by permanently deforming the orifice plate 712 such that the preload on the outlet valve spring 706 is increased and/or the flow between the various plates are restricted.

[0045] A filter support plate 715 defines an opening 716 and is located atop the outlet valve retainer 702, between the outlet valve retainer 702 and the sleeve 621. A filter 714 is located atop the first washer plate 715, between the first washer plate 715 and the sleeve 621. The filter support plate spaces the filter 714 away from the outlet valve retainer, and the opening 716 is sized to increase the flow area for fuel downstream of the filter 714. For example, without the filter support plate 715, the flow area through the filter is defined by the openings of filter 714 projected on the central bore 718; therefore, any debris on the filter 714 reduces the flow area. In contrast, with the filter support plate 715, the flow area through the filter is defined by the openings of filter 714 projected onto the opening 716, which may be a greater area than that of the central bore 718. Accordingly, if part of the filter 714 becomes clogged with debris, the flow area through the filter 714 may still be greater than the flow area of the central bore 718; thus, there would be no substantial loss in overall flow rate.

[0046] A top face plate 701 is located atop the filter 714, between the filter 714 in the sleeve 621. The top face plate 701 is preferably made of a durable material (e.g., metal, steel, stainless steel, brass, etc.) because the inlet valve body 632 and/or the piston end face 639 may contact the top face plate 701 at the bottom of the piston stroke.

[0047] Referring to FIGS. 15 and 16, an outlet valve assembly 800 is shown according to an exemplary embodiment. The outlet valve assembly 800 includes a top face plate 801, a filter 814, and a filter support plate 815. The outlet valve assembly 800 further includes a turbulence generating plate 807 defining a relatively small aperture 808, a washer plate 810 defining a relatively large aperture 809, and an orifice plate 812 defining one or more orifices 811. The plates 801, 815, 807, 810, 812, and the filter 814 are shown to be generally similar to the outlet valve retainer 702, the plates 701, 715, 707, 710, 712, and the filter 714 as described with respect to the outlet valve assembly 700. However, the outlet valve retainer 802, the outlet valve seat body 803, and the outlet valve body 805 are modified to reduce the volume of the sac 830, thereby reducing emissions.

[0048] The outlet valve body 805 is shown to include a lower body portion, shown as ball 832, and a stem, shown as nub 834, extending upward from the ball 832. A flange 836 extends outwardly from the nub 834 and captures the outlet valve spring 806 between the flange 836 and the outlet valve seat body 803. Accordingly, the outlet valve spring 806 is moved from in the sac to above the outlet valve seat body 803, thereby enabling a smaller sac 830. As shown, the ball 832 of the outlet valve body 805 extends into the relatively small aperture 808 and the relative large aperture 809 of the turbulence generating plate 807 and the washer plate 810, respectively. Moving the outlet valve spring 806 out of the sac 830 also enables a smaller outlet valve seat body 803, which is shown to seat against a ledge 838 formed in the central opening 818 of the outlet valve retainer 802.

[0049] During manufacture, the ball 832 and a subassembly including the nub 834 and the outlet valve spring 806 may be assembled to the outlet valve seat body 803 from opposite sides. The ball 832 and the nub 834 may then be fixed together (e.g., resistance welded, etc.), thereby locking together the ball 832, the nub 834, the outlet valve spring 806, and the outlet valve seat body 803. According to another embodiment, the flange 836 (e.g., a cap) may be formed separately from the nub 834, and the ball 832 and the nub 834 may unitarily formed or fixed together. The ball-nub subassembly may be assembled to the outlet valve seat body 803 from one side, and the outlet valve spring 806 and the flange 836 may be assemble to the outlet valve seat body 803 from the other side. The cap or flange 836 may then be fixed to the nub 834 to lock the assembly together. According to another embodiment (not shown), the flange 836 may have a sufficiently small diameter so that the entire flange 836, nub 834, and ball 832 assembly may be inserted during assembly from the bottom. The outlet valve spring 806 may be then snapped into place from the top, facilitated by its elasticity and a conical or rounded top of the flange 836. In such an embodiment, the spring may be conical in shape so that its bottom may rest on the top of the outlet valve seat body 803.

[0050] According to other embodiments, outlet valve designs other than those described above and shown in FIGS. 6-8 and 13-16 may also be used with the injector 10, 610. For example, the outlet valve body 105, 505, 705, 805 can have a variety of shapes, for example, flat plate, conical, poppet, mushroom, semi-spherical, etc. An outward opening pintle-type valve can also be used and can be advantageous because it does not have any sac volume since the sealing area also acts as the metering area. The orifices and structures for improving atomization other than the aforementioned designs may also be used with the fuel injector 10, 610. For example, the orifices 111,511,711,811 can be angled and/or tapered to affect the spray shape. Structures can be employed to introduce swirl to the fuel before reaching the orifices 111, 511, 711, 811. The outlet valve spring 506, 706, 806 can also be a resilient planar member, a spring washer, a solid flexible member, a conical helical spring, etc.

[0051] Referring to FIGS. 1-3, the connector 24 is shown to include a pin 23, which is electrically coupled to a first end of the coil 15 with an electrically conductive lead 22 (e.g., wire, conductor, etc.). A second pin or a second portion of the pin 23 may be coupled to a second end of the coil 15 by a second lead (not shown). The wire leads such as lead 22 are preferably flexible as to prevent fatigue failure and to not impede the motion of the piston 17 and other components that move with it. These "moving components" include the coil 15, the cage 16, the former 38, part of the lead 22, part of the main spring 18, the inlet valve retainer 35, and in some cases the inlet valve body 32 and inlet valve stem 34 by the contact of the inlet valve body 32 against the inlet valve seat 33 or by the transmission of sufficient force by the inlet valve spring 36.

[0052] The connector 24 may be configured as a male or female connector, and is connected to processing electronics (e.g., an electronic control unit (ECU), processing electronics, etc.), which is capable of causing sufficient current to pass through the coil to actuate the injector 10. Referring to FIG. 17, a simplified block diagram of processing electronics 900 is shown, according to an exemplary embodiment. The processing electronics 900 may include a memory 910 and processor 912. The processor 912 may be or include one or more microprocessors, an application specific integrated circuit (ASIC), a circuit containing one or more processing components, a group of distributed processing components, circuitry for supporting a microprocessor, or other hardware configured for processing. According to an exemplary embodiment, the processor 912 is configured to execute computer code stored in the memory 910 to complete and facilitate the activities described herein. The memory 910 can be any volatile or non-volatile memory device capable of storing data or computer code relating to the activities described herein. For example, the memory 910 may include one or more modules 914-924, which are computer code modules (e.g., executable code, object code, source code, script code, machine code, etc.) configured for execution by the processor 912. When executed by the processor, the processing electronics 900 is configured to complete the activities described herein. The processing electronics 900 includes hardware circuitry for supporting the execution of the computer code of the modules 914-924. For example, the processing electronics 900 may include hardware interfaces (e.g., output 930) for communicating control signals (e.g., analog, digital) from the processing electronics 900 to the injector 10, 610 (e.g., pin(s) 23). The processing electronics 900 may also include an input 935 for receiving or sensing data or signals (e.g., feedback signals) from the injector 10, 610 (e.g., pin(s) 23) and from various sensors (e.g., nodes 215, 216 of the circuit of FIG. 18) indicating engine operating conditions (e.g., phase, crank angle, engine speed, engine temperature, coolant temperature, air temperature, etc.).

[0053] Memory 910 includes a memory buffer 914 for receiving injector data, engine data, and user input data. For example, the memory buffer 914 may receive voltage information from node 215, relating the voltage across the coil 15, 615, or node 216, relating to current through the coil 15, 615 (described in in more detail below). The data may be stored in memory buffer 914 until buffer 914 is accessed for data. For example, correlation module 918, injector control module 920, injector priming module 922, self-calibration module 924, or another process may access buffer 914. The data stored in memory 910 may be stored according to a variety of schemes or formats. For example, the data may be stored in an x,y, x,y,z format, or any other suitable format for time-domain or waveform information.

[0054] Memory 910 further includes configuration data 916. Configuration data 916 includes data relating to the injector 10, 610. For example, configuration data 916 may include injector calibration data, which may be data that the correlation module 918 or injector control module 920 can interpret to determine how to command injector 10, 610 to operate. For example, configuration data 916 may include information regarding injector flow rates, injector spray patterns, inductance of the coil, calibration information (e.g., values, tables, curves, etc.) that correlates measured values to other values, for example, coil current to coil velocity and/or coil position, and the like.

[0055] Memory 910 includes a correlation module 918, which includes logic for determining the velocity of the coil 15, 615 through the magnetic field of the injector based on the current through the coil 15, 615, the voltage across the coil 15, 615, and/or the resistance of the coil 15, 615. For example, the correlation module 918 may receive data from the input 935 or the memory buffer 914 and correlate the measured current, voltage, and/or resistance to a velocity using configuration data 916. The correlation module 918 may further determine the position of the piston 17, 617, for example, by integrating the velocity of the coil 15, 615. The correlation module 918 may provide velocity and/or position information to the injector control module 920, injector priming module 922, and the self-calibration module 924.

[0056] Memory 910 includes an injector control module 920, which includes logic for controlling the velocity and/or position of the piston 17, 617 in the injector 10, 610. The injector control module 920 may include a low pressure portion of the stroke sub-module, a high pressure portion of the stroke sub-module, an injection control sub-module, etc. The injector control module 920 may be configured to control the velocity and/or position based on information received from the correlation module 918. The injector control module 920 may output signals to the injector 10, 610 to control the piston 17, 617 via the output 930.

[0057] Memory 910 includes an injector priming module 922, which includes logic for determining whether there is fuel in the injector and for responding to the determination of low or no fuel. The injector priming module 922 may use information from the correlation module 918 and configuration data 916 to determine that there is not fuel in the injector 10, 610, for example, by recognizing voltage, current, or velocity characteristics of the coil described in more detail below. The injector priming module 922 may then provide signals to the injector control module 920 to cause the injector control module 920 to control the injector 10, 610 to operate in such a manner as to draw fuel into the injector 10, 610 (e.g., "prime" the injector 10, 610). The injector priming module 922 may also include logic to determine whether the fuel is boiling or when the injector has no fuel, in which case the injector priming module 922 may provide signals to the injector control module to cause the injector 10, 610 to operate in a low-power or limp-home mode or to shut down the injector 10, 610 completely.

[0058] Memory 910 includes a self-calibration module 924. The self-calibration module may provide signals to the injector control module 920 to cause the injector 10, 610 to operate in a manner such that a baseline information may be gathered. The baseline information may be stored in the configuration data 916. The self-calibration module 924 may include a timer or counter (e.g., counting the number of elapsed injection events), and, after a predetermined period of time or predetermined number of counts (e.g., approximately one million cycles), the self-calibration module 924 may provide signals to the injector control module 920 to cause the injector 10, 610 to operate in a manner such that a second information may be gathered. The self-calibration module 924 may then compare the second information and the baseline information. The self-calibration module 924 may include logic to modify the configuration data 916 or to provide signals to the injector control module 920 such that the injector control module 920 operates in such a manner as to return the performance of the injector 10, 610 to (or substantially near to) the baseline performance of the injector 10. 610.

[0059] A piston pumping cycle is described, with exemplary reference to the injector 10, according to an exemplary embodiment. As shown in FIG. 1, at the start of an injection event, the cage 16 is biased by the main spring 18 to a first or top position against the plate 13. The processing electronics cause a sufficient current in the coil 15, which interacts with the magnetic field in the gap 14 generated by the configuration of the magnet 11, the pole piece 12, and plate 13 to produce a downward force on the coil 15 and a subsequent downward motion of the moving components. The start of an injection event begins with a driving current with a digital (e.g., pulse width modulation (PWM)) signal with less than 100% duty cycle or less than full supply analog level. This low duty cycle driving current does not allow the piston 17 to move fast enough to produce sufficient pressure inside the fluid pumping chamber 40 or move with sufficient acceleration relative to the inlet valve body 32 and stem 34 to overcome the force of the inlet valve spring 36 and thereby close the inlet valve. The initial low speed stroke is long enough so that any vapor present in the fluid pumping chamber 40 exits between the open inlet valve body 32 and inlet valve seat 33 due to the orientation of the injector 10, buoyancy of vapor bubbles, and a positive pressure gradient. According to one embodiment, after a certain length of initial stroke, the driving current increases sufficiently to produce sufficient velocity of the piston 17 to create sufficient pressure inside the fluid pumping chamber 40 to overcome the force of the inlet valve spring 36 and close the inlet valve. According to another embodiment, the driving current may increase sufficiently to accelerate the piston 17 relative to the moving parts of the inlet valve (i.e., inlet valve body 32, inlet valve stem 34, etc.) such that the piston 17 could overcome the force of the inlet valve spring 36 and close the gap between the normally open inlet valve and the piston (i.e., "ram" the piston into the inlet valve). If the closing pressure of the inlet valve is sufficiently high, vapors present in the fluid pumping chamber 40 can also collapse or condense before the inlet valve closes.

[0060] The closing of the inlet valve marks the start of the second fluid pumping stroke, as shown in the position depicted by example in FIG. 2. Thereafter, the pressure inside the fluid pumping chamber 40 increases at a rapid rate, which causes the differential pressure across the outlet valve body 105 to overcome the force of the outlet valve spring 106 and open the outlet valve. That is, the outlet valve opens passively. The opening of the outlet valve allows fuel to flow through the slots 108 in the turbulence generating plate 107, through the turbulence gap 109 in the outlet washer 110, and out of the injector through the orifices 111 in the orifice plate 112. The end of the injection event occurs when the velocity of the piston 17 falls below a rate sufficient to generate a pressure inside the fluid pumping chamber 40 sufficient to keep the outlet valve in an open position, which can happen, for example, when the end face 39 of the piston 17 contacts the top face 101 of the outlet valve retainer 102, or when the current through the coil 15 is not large enough to sustain the sufficient velocity. At the end of an injection event, the processing electronics cause the current to the coil 15 to stop (e.g., cease), which allows the main spring 18 to move the moving components upward until the cage 16 rests against the plate 13 or until a sufficiently large current is again applied through the coil 15. According to one embodiment, the inlet valve opens during the upstroke of the piston 17, thereby allowing fuel to pass through the inlet valve from the piston cavity to fill the fluid pumping chamber 40. According to an embodiment in which the piston 17 does not contact the outlet valve, when the current to the coil 15 is stopped, the velocity of the piston 17 decreases such that the pressure inside the fluid pumping chamber 40 drops below the cracking pressure of the outlet valve.

[0061] Referring now to FIG. 18, a circuit used to control and sense the injector 10 is shown, according to an exemplary embodiment. A voltage supply is connected to node 201 which is connected to the source of a transistor 202. As shown, the transistor 202 is a P-channel MOSFET. The gate 203 of the transistor 202 may be controlled by the processing electronics or a portion thereof, for example, by a digital signal from a microprocessor, either directly or through one or more other amplifiers. The drain of the transistor 202 is connected one end (e.g., a first end) of the coil 204, while the other end (e.g., a second end) of the coil 204 is connected to one end (e.g., a first end) of the current sense resistor 207. This coil 204 refers to the same coil 15, 615 in FIGS. 1-4, 10-12, which has its own resistance and inductance. The other end (e.g., the second end) of the current sense resistor 207 is connected to a ground 208. A small capacitor 206 and a diode 205 with its cathode connected to the drain of the transistor 202 are shown connected in parallel with the coil 204. A first operational amplifier 209 measures the voltage across the coil 204 and outputs (e.g., provides a signal) to node 215. The values of the resistor 211 and resistor 210 set the gain of the operational amplifier 209. A second operational amplifier 212 measures the voltage across the current sense resistor 207 and outputs to node 216. The values of the resistor 214 and the resistor 213 set the gain of the operational amplifier 212.

[0062] Before the start of an injection cycle, the signal at the gate 203 of the transistor 202 is greater than the threshold which does not allow current to pass through from the source of the transistor 202 to its drain. At the start of an injection cycle, a low signal is sent to the gate 203 of the transistor 202 such that it is operating in saturation after a small amount of time, which allows current to flow from its source to its drain. The voltage at the top end of the coil 204 is now at the supply voltage of node 201 minus the voltage drop across the transistor 202, which causes current to travel through the coil 204 and the current sense resistor 207 to the ground 208. When it is desired to stop current through the coil 204, the signal at the gate 203 of the transistor 202 is raised to above the threshold which stops current flow from the source to the drain. Due to the inductance of the coil 204, its current does not stop immediately but flows through the diode 205 for a short time during which energy stored in the magnetic field of the coil 204 is dissipated through the resistance of the coil 204. An additional resistor can be added in series with the diode 205 to reduce the time to dissipate the energy through the coil 204. The diode 205 is known as a "freewheeling" diode, which protects the drain of the transistor 202 from large negative transient voltages due to the inductance of the coil 204. The capacitor 206 prevents a large spike in voltage because the diode 205 has a small but finite turn-on time. The first and second operational amplifiers 209 and 212 can be used to sense the voltages across the coil 204 and current sense resistor 207 at any time. The outputs nodes 215 and 216 can be output to (e.g., received by) processing electronics or a portion thereof, for closed-loop control of the coil 204.

[0063] The circuit mentioned above is only one method of driving and sensing the coil 204. There exists other methods that are capable of achieving the same, such as with the use of another type of transistor (e.g., a field effect transistor (e.g., an N-channel MOSFET, a JFET, etc.)), a bipolar junction transistor, etc., with appropriate modifications to the circuit. Alternatively, the voltage from the current sense resistor 207 can be used to provide a current controlled source using negative feedback.

[0064] Referring to FIG. 18, the voltage across the coil 15, 204 is measured by a first operational amplifier 209, shown, for example, in FIG. 18, during an injection event using a first method of control can be seen in waveform 301, according to an exemplary embodiment. At the start of an injection event at instance 303, a large pulse 304 is caused in the coil by the processing electronics. The large pulse is of sufficient width to bring the velocity of the coil 15 close to a target value. At instance 305, the processing electronics cause the voltage to cease across the coil 15, which causes a negative voltage spike 306 due to the inductance of the coil 15. Before instance 307, all existing energy stored in the magnetic field of the coil 15 has been dissipated and a back EMF voltage 308 is generated across the now "floating" coil corresponding to the velocity of the coil 15. The processing electronics may read (e.g., receive, receive a signal corresponding to, etc.) the voltage 308 and compares it with a target value. In response, the processing electronics may make changes to the pulse width of the control pulse 309 defined by the time between instance 307 and instance 315 to correct for any errors. For example, the processing electronics may add and control extra pause time after the instance 307 to correct for errors in the coil velocity. According to some embodiments, the analog level or duty cycle of the control pulse 309 can be controlled to correct for errors in the coil velocity as well. The velocity target value can be a fixed value or can vary. For example, the processing electronics may vary the velocity target value in response to sensor inputs, which can be indicative of engine operating conditions, for example, engine speed, temperature, and load. According to one embodiment, the velocity target value(s) may be stored in the memory of the processing electronics. During the pause time, the velocity of the coil 15 is reduced due to drag forces and the force from the main spring 18 but is still positive so that the coil 15 continues to move downwards. As shown in FIG. 18, there can be a large number of pause and control pulse cycles during this initial low pressure portion of the stroke. While the voltage 308 of the waveform 301 is shown to be constant, in practice, the level of the voltage 308 may increase or decrease for after each pulse due to the velocity of the coil 15.

[0065] At the instance 310, the high pressure pulse 311 begins. At some instance shortly after the instance 310, the velocity of the piston 17 reaches a sufficient speed in order to generate sufficient pressure inside the fluid pumping chamber 40 or sufficiently accelerate the piston relative to the valve body and stem to cause the inlet valve to close and the outlet valve to subsequently open, which marks the beginning of the high pressure portion of the stroke. The arrangement of the mechanical components during the high pressure portion of the stroke can be seen, for example, in FIG. 2. At the instance 312, the current applied to the coil 15 is stopped, which allows the coil 15 and the moving components to begin traveling upward due to the biasing force of the main spring 18. At the instance 313, the cage 16 has come in contact with the plate 13 and is shown to experience some oscillations which can be seen in the back EMF oscillations 314. At the instance 302, the injector 10 has completed an injection event or cycle and is ready to for the next event or cycle.

[0066] Using the waveform in FIG. 19 or some variations thereof, the amount of fuel being injected per stroke can be controlled by varying the piston travel distance of the initial low pressure portion of the stroke. For example, the processing electronics may be configured to cause a long low pressure portion of the stroke, thereby allowing liquid and vapor fuel to pass out of the fluid pumping chamber 40 through the inlet valve before beginning the high pressure portion of the stroke, which reduces the remaining fuel in the fluid pumping chamber 40 available to be injected during that stroke. The processing electronics may cause a high duty cycle ejection pulse of sufficient width so that the end face 39 of the piston 17 contacts the top face 101 of the outlet valve retainer 102. The length of the initial low pressure portion of the stroke can be varied by changing the number of pause and control pulses, the target velocity at each pause pulse, or some combination thereof.

[0067] The system and method described with respect to the waveform of FIG. 19 is particularly advantageous for control because it allows several feedback loops to take place during a single injection event to precisely meter the amount of fuel being injected. Further, because the voltage 308 corresponds to the velocity of the coil 15, and thus the velocity of the piston 17, the processing electronics may determine a position or displacement (e.g., length of stroke thus far, distance traveled from the start of the cycle, etc.) of the piston 17 by integrating the voltages 308 or corresponding velocities. The processing electronics may then use the position or displacement information to control the amount of fuel injected per stroke. Another advantage of the system and method described with respect to the waveform of FIG. 19 is that fuel metering is based on positive displacement, which provides consistent metering independent from factors such as variations in the manifold pressure, variations in the orifice sizes due to manufacturing tolerances and/or formed deposits with use, variations in the friction and drag of the moving components, and variations in the force produced by the coil. A low pressure portion of the stroke module in the processing electronics may be configured to control the injector 10 as described above with respect to FIG. 19.

[0068] Referring now to FIG. 20, the voltage across a current sense resistor 207, shown for example in FIG. 18, during an injection event using a second method of control can be seen in the waveform 401 and the waveform 402, according to exemplary embodiments. The voltage across the current sense resistor 207 is proportional to the amount of current flowing through the coil 15, 204 when the current flows from the drain of the transistor 202 to the ground 208, as shown in FIG. 18. Waveform 401 represents the voltage across the current sense resistor 207 in an injection event in which little or no liquid fuel is inside the fluid pumping chamber 40. Waveform 402 represents the voltage across the current sense resistor 207 in an injection event in which the fluid pumping chamber 40 is substantially filled with liquid fuel.

[0069] At the start of an injection event at the instance 403, the processing electronics cause a voltage to be applied across the coil 15, 204 with a low duty cycle until the instance 404. During this time, the piston 17 does not move with sufficient velocity to generate sufficient pressure in the fluid pumping chamber 40 or sufficiently accelerate the piston relative to the valve body and stem to close the inlet valve. According to another embodiment, the initial low duty cycle stroke is omitted in this second method of control. At the instance 404, the high duty cycle pulse begins. The current through the coil 15, 204 takes some finite time to increase due to the inductance of the coil, reaching its maximum level at instance 405. After instance 404, the speed of the coil 15, 204 increases substantially, which is responsible for the reduction in the voltage after instance 405. An increase in coil speed leads to a reduction in the current through the coil 15, 204 and subsequently a reduction in the voltage across the current sense resistor 207 due to the back EMF generated by the moving coil.

[0070] For the waveform 402, at instance 406 the voltage increases sharply because the piston 17 has sufficient speed to generate sufficient pressure inside the fluid pumping chamber 40 or sufficiently accelerate the piston relative to the valve body and stem to close the inlet valve, which further increases the pressure and decelerates the piston 17 and coil 15 velocity. When a sufficient pressure (which may be the same or greater than the pressure to close the inlet valve) is reached inside the pumping chamber, the outlet valve opens. The closing of the inlet valve and/or opening of the outlet valve marks the beginning of the high pressure portion of the stroke. At some time after the high pressure portion of the stroke begins, the velocity of the coil 15 slows down to some steady value greater than zero, which can be observed by the voltage level 410. According to the exemplary embodiment shown, at the instance 411, the end face 39 of the piston 17 impacts the bottom of the pumping chamber (e.g., the top face 101 of the outlet valve retainer 102), causing oscillations 412 in the waveform 402. After the oscillations 412, the piston 17 comes to a rest, which can be seen in the shift of the voltage from voltage level 410 to voltage level 409. At the instance 413, the high duty cycle pulse stops and the voltage rapidly falls to zero.

[0071] For the waveform 401, since there is no liquid fuel inside the fluid pumping chamber 40, fuel vapor or air in the fluid pumping chamber 40 does not generate significant pressure when it is pushed (e.g., squeezed, forced, etc.) out of the fluid pumping chamber 40 through the inlet valve. Accordingly, the inlet valve does not close. Instead, according to the embodiment shown, the current in waveform 401 increases sharply at the instance 407 when the end face 39 of the piston 17 contacts the top face 101 of the outlet valve retainer 102 and rebounds (e.g., bounces), which can be seen in the oscillations 408. As shown, the high duty cycle pulse is still being applied after the oscillations prior to instance 411, thereby causing the piston 17 to remain in contact with (e.g., rest against, press against, push against, etc.) the outlet valve retainer 102 and causing the voltage of the corresponding waveform 401 to be at the voltage level 409. At the instance 413, the high duty cycle pulse stops and the voltage rapidly falls the zero.

[0072] As described with respect to the waveform 401, the processing electronics may be configured to determine when liquid is not being pumped. Accordingly, the processing electronics may be configured to run the injector for a predetermined number of cycles or a predetermined amount of time in an attempt to prime the injector. As described above, residual fuel fluid in the fluid pumping chamber 40 reduces the impact of the piston 17 on the outlet valve. Accordingly, the processing electronics may be configured to cease operation of the injector after the predetermined number of cycles or predetermined amount of time. The predetermined number of cycles or predetermined amount of time may correlate to the cycles or time necessary to pump fluid from a tank to the injector. An injector priming module in the processing electronics may be configured to control the injector 10 as described above.

[0073] For both the 401 and 402 waveforms, the voltage level 409 is equal to the supply voltage multiplied by the ratio of the resistance of the current sense resistor 207 over the sum of the resistance of the current sense resistor 207, the resistance of the transistor 202, and the resistance of the coil 204. During operation of the injector 10, the temperature of the coil 15, 204, the current sense resistor 207, and the transistor 202 rises, thereby changing the resistances thereof. Specifically, the resistance of the coil 15, 204 rises; thus, for a given current through the coil 15, 204, the voltage across the coil 15, 204 increases, and for a given voltage across the coil 15, 204, the current through the coil 15, 204 decreases. Accordingly, the processing electronics may control the voltage across, or current through, the coil 15, 204 in response to the temperature of the coil 15. For example, the processing electronics may control the voltage across the coil 15, 204, for example, at node 201, in response to the voltage level 409. Furthermore, instead of using the voltage level 409, a dedicated circuitry may be used to measure the resistance of the coil directly at regular intervals by, for example, driving the coil with a known voltage substantially small as to not overcome the force of the mainspring and measuring the current through the coil. According to one embodiment, a self-calibration module in the processing electronics may be configured to determine, provide, and/or store updated current or voltages values in response to the temperature change in the coil 15. The processing electronics may further be configured to stop current to the coil 15 when a voltage at voltage level 409 is sensed, thereby reducing cycle times and possibly reducing wear on the components. The processing electronics may further be configured to calculate the time between instance 312 and instance 313, which is the time required for the main spring 18 to accelerate the moving components until the cage 16 makes contact with the plate 13. This time may be used to calculate the piston stroke length of the previous stroke, or may be used to indicate abnormal operation. For example, if the fluid pumping chamber or injector is not substantially full of fuel, the drag and pressure forces on the moving components will be reduced, and the time between instance 312 and instance 313 will be reduced.

[0074] For both 401 and 402 waveforms, the total length of the high pressure portion of the stroke can be determined by the time between when the voltage first increases rapidly to when it reaches the voltage level 409. For example, for waveform 401, the time is nearly zero, and for waveform 402, the time is between the instance 406 and instance 411. In an alternative method of control, the voltage applied across the coil can be stopped before the piston is stopped by the outlet valve retainer in which case the length of the high pressure portion of the stroke can be determined by the time between when the voltage first increases rapidly to when the current is stopped. This method of control is pressure driven rather than of the positive displacement type. In this method of control, the initial low duty cycle pulse is not required for metering.

[0075] The system and method described with respect to the waveform of FIG. 20 is advantageous for control because it is able to sense the velocity of the coil without stopping the current through the coil, which allows processing electronics with a high sampling rate to be used. Thus, the processing electronics is able to determine with great precision when the inlet valve closes and the high pressure portion of the stroke begins, when the end face of the piston impacts the top face of the outlet valve retainer, and if these events happen. Using this information, the processing electronics can potentially self-calibrate itself to spray the correct amount of fuel despite variations in the manufacturing of the fuel injector and in the circuit components. For example, a self-calibration module in the processing electronics may be configured to determine, provide, and/or store updated values. The processing electronics can also use self-calibration to correct for the drift in the flow rate of the injector during use due to factors such as wear, orifice fouling, demagnetization, etc. For example, when the injector is new, the length of time between the detected inlet valve closing event and the detected piston impact event will be shorter than at some later time if, for example, the orifice plate becomes clogged or fouled and the flow rate becomes reduced. The processing electronics can be programmed to perform a self-calibration cycle on a regular basis in which the aforementioned time is measured, and then to adjust the fuel calibration values accordingly to account for the change in flow rate. For example, the processing electronics may compare a baseline length of injection with a length of injection at n*predetermined-value cycles to determine if there is a change in flow rate through the injector. If there is a change in flow rate, the processing electronics may calibrate, for example, configuration data stored in a memory to compensate for the change in flow rate. This feature may be useful for low cost applications in which an oxygen sensor that can normally provide self-calibration is not used. Furthermore, the processing electronics can determine when there is no fuel inside the fluid pumping chamber such as during hot soak conditions and activate a series of rapid strokes to prime the pump or shut off to prevent overheating of the injector. A high pressure portion of the stroke module in the processing electronics may be configured to control of the injector 10 as described above with respect to FIG. 20.

[0076] Furthermore, as described above with respect to FIG. 20, the process electronics may be able to sense the closing of the inlet valve. According to some embodiments, the inlet valve can only close when the fluid pumping chamber is nearly completely full of fuel. Thus, control of the initial low pressure portion of the stroke, as described with respect to FIG. 19, may not be necessary. According to other embodiments, the systems and methods for FIG. 20 may be used by the processing electronics to determine when to begin the long pulse width corresponding to the high pressure portion of the stroke (e.g., instance 310 as shown in FIG. 19).

[0077] The control and sensing methods described with regards to the waveforms of FIG. 19 and FIG. 20 may be used separately or in conjunction. In one method, the length of the initial low pressure portion of the stroke is varied as described with respect to FIG. 19. In a second method of control, the length of the initial low pressure portion of the stroke is fixed or not controlled while the length of the second high duty cycle stroke is controlled as described with respect to FIG. 20. For example, the length of the second high duty cycle stroke can be controlled by varying the corresponding pulse width. After the current to the coil is stopped, the pressure inside the fluid pumping chamber 40 drops below the cracking pressure of the outlet valve almost immediately. A small amount of fuel may still be injected after the current in the coil is stopped due to the inertia of the moving components.

[0078] Referring to FIGS. 21-22, a flowchart of a process 1000 for controlling a fuel injection system is shown according to an exemplary embodiment. The process 1000 may include the step of determining a baseline elapsed time between a start of injection and an end of injection (step 1001). Step 1001 is a baseline step and may be performed in the factory before shipment or in the field after a predetermined number of cycles (e.g., after break-in of the injector). The process 1000 is shown to include the steps of measuring a current through a coil in the fuel injector (step 1004), receiving the measured current (step 1006), and determining at least one of a velocity and a position of the coil through a magnetic field by correlating the measured current, resistance, and voltage to the velocity of the coil (step 1008). According to one embodiment the current through the coil may be measured by measuring a voltage across a current sense resistor. The process 1000 is further shown to include the steps of controlling the current through the coil in response to at least one of the velocity and the position of the coil (step 1010) and determining a start of injection (step 1012). Determining the start of injection may be based, for example, on a change in measured voltage, a change in measured current, or a change in velocity of the coil. The process 1000 determines whether the fuel is rapidly vaporizing (step 1014), for example, based on the start of injection (e.g., a timing of the start of injection). If fuel is rapidly vaporizing, the current through the coil is controlled to compensate for the fuel vapor (step 1016).

[0079] Referring to FIG. 22, the process 1000 is shown to include the steps of determining the end of injection (step 1018) and increasing a cycle counter by one (step 1020). Determining the end of injection may be based, for example, on a change in measured voltage, a change in measured current, a change in velocity of the coil, or a controlled discontinuation of current through the coil. The process 1000 determines whether there is fuel in the injector (step 1022), for example, based on the end of injection (e.g., a timing of the end of injection). If there is not fuel in the injector, the injector may be shut down (step 1024) and/or the injector may be primed with fuel (step 1026) before beginning again (1002). If there is fuel in the injector, the process 1000 determines whether the cycle counter is equal to a predetermined value (step 1028). If not, then the process begins again (1002). If so, then a calibration pulse is performed where the current through the coil is held sufficiently long so that the piston bottoms out (e.g., reaches maximum stroke, contacts the bottom of the pumping chamber, etc.), and the process determines a second elapsed time between a start of injection and the end of injection (step 1030). The process 1000 compares the second elapsed time with the baseline elapsed time to determine if the flow rate through the injector has changed (step 1032). If the flow rate has changed, the process 1000 calibrates the control system (step 1034) before beginning again (1002). If the flow rate has not changed, the process 1000 begins again (1002).

[0080] The construction and arrangement of the elements of the fuel injection system as shown in the exemplary embodiments are illustrative only. Although only a few embodiments of the present disclosure have been described in detail, those skilled in the art who review this disclosure will readily appreciate that many modifications are possible (e.g., variations in sizes, dimensions, structures, shapes and proportions of the various elements, values of parameters, mounting arrangements, use of materials, colors, orientations, etc.) without materially departing from the novel teachings and advantages of the subject matter recited. For example, elements shown as integrally formed may be constructed of multiple parts or elements. The elements and assemblies may be constructed from any of a wide variety of materials that provide sufficient strength or durability, in any of a wide variety of colors, textures, and combinations. Additionally, in the subject description, the word "exemplary" is used to mean serving as an example, instance, or illustration. Any embodiment or design described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other embodiments or designs. Rather, use of the word "exemplary" is intended to present concepts in a concrete manner. Accordingly, all such modifications are intended to be included within the scope of the present disclosure. Other substitutions, modifications, changes, and omissions may be made in the design, operating conditions, and arrangement of the preferred and other exemplary embodiments without departing from the scope of the appended claims.

[0081] The present disclosure contemplates methods, systems and program products on any machine-readable media for accomplishing various operations. The embodiments of the present disclosure may be implemented using existing computer processors, or by a special purpose computer processor for an appropriate system, incorporated for this or another purpose, or by a hardwired system. Embodiments within the scope of the present disclosure include program products comprising machine-readable media for carrying or having machine-executable instructions or data structures stored thereon. Such machine-readable media can be any available media that can be accessed by a general purpose or special purpose computer or other machine with a processor. By way of example, such machine-readable media can comprise RAM, ROM, EPROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to carry or store desired program code in the form of machine-executable instructions or data structures and which can be accessed by a general purpose or special purpose computer or other machine with a processor. When information is transferred or provided over a network or another communications connection (either hardwired, wireless, or a combination of hardwired or wireless) to a machine, the machine properly views the connection as a machine-readable medium. Thus, any such connection is properly termed a machine-readable medium. Combinations of the above are also included within the scope of machine-readable media. Machine-executable instructions include, for example, instructions and data which cause a general purpose computer, special purpose computer, or special purpose processing machines to perform a certain function or group of functions.

[0082] The order or sequence of any process or method steps may be varied or re-sequenced according to alternative embodiments. Any means-plus-function clause is intended to cover the structures described herein as performing the recited function and not only structural equivalents, but also equivalent structures. Other substitutions, modifications, changes and omissions may be made in the design, operating configuration, and arrangement of the preferred and other exemplary embodiments without departing from the scope of the appended claims.

Claims

1. A fuel injector (10), comprising:

a sleeve (21) having a first end proximate an outlet;
a piston (17) slidingly received in the sleeve (21), the piston (17) having a first end proximate the outlet;
a pumping chamber (40) at least partially defined by the sleeve (21) between the first end (39) of the piston (17) and the outlet; and
a normally-open valve (50) through which fuel passes to enter or exit the pumping chamber (40);
wherein the normally-open valve (50) closes in response to a movement of the piston (17); and wherein the normally-open valve (50) closes when the piston (17) has sufficient velocity to create sufficient pressure inside the fluid pumping chamber (40) or the piston (17) has sufficient acceleration to close the normally-open valve (50).

2. The fuel injector of claim 1, wherein the normally open valve (50) comprises an inlet valve coupled to the first end of the piston (17).

3. The fuel injector of claim 1, wherein the normally-open valve (50) comprises a valve body (32) biased away from a valve seat (33) by a valve spring (36), and wherein the normally-open valve (50) closes when the piston (17) has sufficient velocity to create sufficient pressure inside the fluid pumping chamber (40) or the piston (17) has sufficient acceleration relative to the valve body (32) to overcome the force of the valve spring (36).

4. The fuel injector of any of claims 1-3, wherein the outlet comprises a normally-closed outlet valve coupled to the first end of the sleeve (21).

5. The fuel injector of claim 4, wherein the piston (17) is slidable between a first position and a second position, and wherein movement of the piston (17) from the second position to the first position forces fluid from the pumping chamber (40) through the outlet valve, and movement of the piston (17) from the first position to the second position draws fluid into the pumping chamber (40) through the valve.

6. The fuel injector of any of claims 1-5, wherein the piston (17) is slidable between a first position and a second position, and wherein reciprocation of the piston (17) between the first and second positions causes the fuel injector to act as a positive displacement or impulse pressure pump.

7. The fuel injector of any of claims 1-6, wherein the piston (17) comprises a pistonwall coupled to the inlet valve (50), the wall and the inlet valve at least partially defining a cavity in the piston (17), wherein fuel passes through the cavity to enter the pumping chamber (40).

8. The fuel injector of any of claims 1-7, comprising a magnetic actuation assembly supported by the housing and coupled to the piston (17), the magnetic actuation assembly comprising at least one magnet (11) and a coil (15) and configured to translate the piston (17).

9. The fuel injector of any of claims 1-8, comprising an electromagnetic actuation assembly, the electromagnetic actuation assembly comprising:

one or more magnets (11) having a magnetic field;
one or more pieces (12, 13) of low reluctance material to focus the magnetic field of the one or more magnets (11) across one or more high reluctance gaps;
a wire coil (15) situated at least partially in one or more high reluctance gaps such that, when a current is applied to the wire coil (15), the current interacts with the magnetic field to produce a force.

10. The fuel injector of any of claims 1-9, comprising a piston assembly, the piston assembly including:

a piston (17) including:

a piston wall extending from a first end of the piston (17) and at least partially defining a piston cavity; and
a valve seat (33) located at the first end of the piston (17);

an inlet valve (50) coupled to the piston (17) comprising a poppet, the poppet including:

a valve body (32) configured to seal against the valve seat (33); and
a valve stem (34) extending from the valve body;

a retainer (35) coupled to the valve stem (34) and configured to limit the travel of the poppet relative to the piston (17); and
a valve spring (36) coupled to the piston (17) and biasing the poppet towards one of a normally-open and a normally-closed valve position.

11. The fuel injector of any of claims 1-10, comprising an outlet valve assembly (100), the outlet valve assembly including:

an outlet valve comprising:

a valve seat (104);
a valve body (103); and
a spring (106) biasing the valve body (103) against the valve seat (104) such that the outlet valve assembly (100) is normally closed;

wherein the outlet valve opens passively under pressure.

12. The fuel injector of any of claims 1-11, comprising a control system and an electromagnetic coil configured to move the piston (17).

Patentansprüche

1. Kraftstoffeinspritzventil (10), umfassend:

eine Hülse (21) mit einem ersten Ende in der Nähe eines Auslasses;
einen Kolben (17), der gleitend in der Hülse (21) aufgenommen ist, wobei der Kolben (17) ein erstes Ende in der Nähe des Auslasses aufweist;
eine Pumpenkammer (40), die zumindest teilweise durch die Hülse (21) zwischen dem ersten Ende (39) des Kolbens (17) und dem Auslass definiert ist; und
ein normalerweise offenes Ventil (50), durch das Kraftstoff läuft, um in die Pumpenkammer (40) einzutreten oder aus ihr auszutreten;
wobei das normalerweise offene Ventil (50) als Reaktion auf eine Bewegung des Kolbens (17) schließt; und
wobei das normalerweise offene Ventil (50) schließt, wenn der Kolben (17) eine ausreichende Geschwindigkeit aufweist, um einen ausreichenden Druck innerhalb der Fluidpumpenkammer (40) zu erzeugen, oder der Kolben (17) eine ausreichende Beschleunigung aufweist, um das normalerweise offene Ventil (50) zu schließen.

2. Kraftstoffeinspritzventil nach Anspruch 1, wobei das normalerweise offene Ventil (50) ein mit dem ersten Ende des Kolbens (17) gekoppeltes Einlassventil umfasst.

3. Kraftstoffeinspritzventil nach Anspruch 1, wobei das normalerweise offene Ventil (50) einen Ventilkörper (32) umfasst, der durch eine Ventilfeder (36) von einem Ventilsitz (33) weg vorgespannt ist, und wobei das normalerweise offene Ventil (50) schließt, wenn der Kolben (17) eine ausreichende Geschwindigkeit aufweist, um einen ausreichenden Druck innerhalb der Fluidpumpenkammer (40) zu erzeugen, oder der Kolben (17) eine ausreichende Beschleunigung relativ zum Ventilkörper (32) aufweist, um die Kraft der Ventilfeder (36) zu überwinden.

4. Kraftstoffeinspritzventil nach Anspruch 1, wobei der Auslass ein mit dem ersten Ende der Hülse (21) gekoppeltes normalerweise geschlossenes Auslassventil umfasst.

5. Kraftstoffeinspritzventil nach Anspruch 4, wobei zwischen einer ersten Position und einer zweiten Position verschiebbar ist und wobei die Bewegung des Kolbens (17) von der zweiten Position in die erste Position Fluid aus der Pumpenkammer (40) durch das Auslassventil zwingt und eine Bewegung des Kolbens (17) von der ersten Position in die zweite Position Fluid durch das Ventil in die Pumpenkammer (40) saugt.

6. Kraftstoffeinspritzventil nach einem der Ansprüche 1-5, wobei der Kolben (17) zwischen einer ersten Position und einer zweiten Position verschiebbar ist und wobei eine Hinundherbewegung des Kolbens (17) zwischen der ersten und der zweiten Position bewirkt, dass das Kraftstoffeinspritzventil als eine Verdrängungs- oder Impulsdruckpumpe wirkt.

7. Kraftstoffeinspritzventil nach einem der Ansprüche 1-6, wobei der Kolben (17) eine mit dem Einlassventil (50) gekoppelte Kolbenwand aufweist, wobei die Wand und das Einlassventil zumindest teilweise einen Hohlraum in dem Kolben (17) definieren, wobei Kraftstoff durch den Hohlraum läuft, um in die Pumpkammer (40) einzutreten.

8. Kraftstoffeinspritzventil nach einem der Ansprüche 1-7, umfassend eine magnetische Betätigungsanordnung, die durch das Gehäuse gestützt und mit dem Kolben (17) gekoppelt ist, wobei die magnetische Betätigungsanordnung mindestens einen Magneten (11) und eine Spule (15) umfasst und zum

Verschieben des Kolbens (17) konfiguriert ist.

9. Kraftstoffeinspritzventil nach einem der Ansprüche 1-8, umfassend eine elektromagnetische Betätigungsanordnung, wobei die elektromagnetische Betätigungsanordnung umfasst:

einen oder mehrere Magnete (11) mit einem Magnetfeld;
ein oder mehrere Stücke (12, 13) aus Material mit geringer Reluktanz, um das Magnetfeld des einen oder der mehreren Magnete (11) über einen oder mehrere Spalten hoher Reluktanz zu fokussieren;
eine Drahtspule (15), die zumindest teilweise in einem oder mehreren der Spalten hoher Reluktanz angeordnet ist, sodass, wenn ein Strom an die Drahtspule (15) angelegt wird, der Strom mit dem Magnetfeld zusammenwirkt, um eine Kraft zu erzeugen.

10. Kraftstoffeinspritzventil nach einem der Ansprüche 1-9, umfassend eine Kolbenanordnung, wobei die Kolbenanordnung umfasst:

einen Kolben (17), umfassend:

eine Kolbenwand, die sich von einem ersten Ende des Kolbens (17) erstreckt und zumindest teilweise einen Kolbenhohlraum definiert; und
einen Ventilsitz (33) der sich am ersten Ende des Kolbens (17) befindet;
ein Einlassventil (50), das mit dem Kolben (17) gekoppelt ist und einen Ventilkegel umfasst, wobei der Ventilkegel umfasst:

einen Ventilkörper (32), der dazu konfiguriert ist, gegen den Ventilsitz (33) abzudichten; und
eine Ventilstange (34), die sich von dem Ventilkörper erstreckt;
einen Halter (35), der mit der Ventilstange (34) gekoppelt und so konfiguriert ist, dass er den Hub des Ventilkegels relativ zu dem Kolben (17) begrenzt; und
eine Ventilfeder (36), die mit dem Kolben (17) gekoppelt ist und den Ventilkegel in Richtung einer normalerweise offenen und einer normalerweise geschlossenen Ventilstellung vorspannt.

11. Kraftstoffeinspritzventil nach einem der Ansprüche 1-10, umfassend eine Auslassventilanordnung (100), wobei die Auslassventilanordnung umfasst:

ein Auslassventil, umfassend:

einen Ventilsitz (104);
einen Ventilkörper (103); und
eine Feder (106), die den Ventilkörper (103) gegen den Ventilsitz (104) so vorspannt, dass die Auslassventilanordnung (100) normalerweise geschlossen ist;

wobei das Auslassventil unter Druck passiv öffnet.

12. Kraftstoffeinspritzventil nach einem der Ansprüche 1-11, umfassend ein Steuersystem und eine elektromagnetische Spule, die zum Bewegen des Kolbens (17) konfiguriert ist.

Revendications

1. Injecteur de carburant (10), comprenant :

un manchon (21) ayant une première extrémité à proximité d'une sortie ;
un piston (17) reçu de manière coulissante dans le manchon (21), le piston (17) ayant une première extrémité à proximité de la sortie ;
une chambre de pompage (40) définie au moins partiellement par le manchon (21) entre la première extrémité (39) du piston (17) et la sortie ; et
une soupape normalement ouverte (50) à travers laquelle du carburant passe pour entrer dans ou sortir de la chambre de pompage (40) ;
la soupape normalement ouverte (50) se fermant en réponse à un mouvement du piston (17) ; et
la soupape normalement ouverte (50) se fermant lorsque le piston (17) a une vitesse suffisante pour créer une pression suffisante à l'intérieur de la chambre de pompage de fluide (40) ou le piston (17) a une accélération suffisante pour fermer la soupape normalement ouverte (50).

2. Injecteur de carburant selon la revendication 1, dans lequel la soupape normalement ouverte (50) comprend une soupape d'entrée couplée à la première extrémité du piston (17).

3. Injecteur de carburant selon la revendication 1, dans lequel la soupape normalement ouverte (50) comprend un corps de soupape (32) sollicité à l'opposé d'un siège de soupape (33) par un ressort de soupape (36), et la soupape normalement ouverte (50) se ferme lorsque le piston (17) a une vitesse suffisante pour créer une pression suffisante à l'intérieur de la chambre de pompage de fluide (40) ou le piston (17) a une accélération suffisante par rapport au corps de soupape (32) pour surmonter la force du ressort de soupape (36).

4. Injecteur de carburant selon l'une quelconque des revendications 1 à 3, dans lequel la sortie comprend une soupape de sortie normalement fermée couplée à la première extrémité du manchon (21).

5. Injecteur de carburant selon la revendication 4, dans lequel le piston (17) est apte à coulisser entre une première position et une seconde position, et un mouvement du piston (17) de la seconde position à la première position forçant du fluide à partir de la chambre de pompage (40) à travers la soupape de sortie, et un mouvement du piston (17) de la première position à la seconde position aspirant du fluide dans la chambre de pompage (40) par l'intermédiaire de la soupape.

6. Injecteur de carburant selon l'une quelconque des revendications 1 à 5, dans lequel le piston (17) est apte à coulisser entre une première position et une seconde position, et un mouvement de va-et-vient du piston (17) entre les première et seconde positions amenant l'injecteur de carburant à agir comme pompe volumétrique ou à impulsion.

7. Injecteur de carburant selon l'une quelconque des revendications 1 à 6, dans lequel le piston (17) comprend une paroi de piston couplée à la soupape d'entrée (50), la paroi et la soupape d'entrée définissant au moins partiellement une cavité dans le piston (17), du carburant passant à travers la cavité pour entrer dans la chambre de pompage (40).

8. Injecteur de carburant selon l'une quelconque des revendications 1 à 7, comprenant un ensemble d'actionnement magnétique supporté par le boîtier et couplé au piston (17), l'ensemble d'actionnement magnétique comprenant au moins un aimant (11) et une bobine (15) et étant configuré pour déplacer le piston (17) en translation.

9. Injecteur de carburant selon l'une quelconque des revendications 1 à 8, comprenant un ensemble d'actionnement électromagnétique, l'ensemble d'actionnement électromagnétique comprenant :

un ou plusieurs aimants (11) ayant un champ magnétique ;
un ou plusieurs éléments (12, 13) de matériau de faible réluctance pour concentrer le champ magnétique du ou des aimants (11) à travers un ou plusieurs entrefers de haute réluctance ;
une bobine de fil (15) située au moins partiellement dans un ou plusieurs entrefers de haute réluctance de telle sorte que, lorsqu'un courant est appliqué à la bobine de fil (15), le courant interagit avec le champ magnétique pour produire une force.

10. Injecteur de carburant selon l'une quelconque des revendications 1 à 9, comprenant un ensemble piston, l'ensemble piston comprenant :

un piston (17) comprenant :

une paroi de piston s'étendant à partir d'une première extrémité du piston (17) et définissant au moins partiellement une cavité de piston ; et
un siège de soupape (33) situé à la première extrémité du piston (17) ;

une soupape d'entrée (50) couplée au piston (17) comprenant un champignon, le champignon comprenant :

un corps de soupape (32) configuré pour assurer une fermeture étanche contre le siège de soupape (33) ; et
une tige de soupape (34) s'étendant à partir du corps de soupape ;

un élément de retenue (35) couplé à la tige de soupape (34) et configuré pour limiter la course du champignon par rapport au piston (17) ; et
un ressort de soupape (36) couplé au piston (17) et sollicitant le champignon vers l'une d'une position de soupape normalement ouverte et d'une position de soupape normalement fermée.

11. Injecteur de carburant selon l'une quelconque des revendications 1 à 10, comprenant un ensemble soupape de sortie (100), l'ensemble soupape de sortie comprenant :

une soupape de sortie comprenant :

un siège de soupape (104) ;
un corps de soupape (103) ; et
un ressort (106) sollicitant le corps de soupape (103) contre le siège de soupape (104) de telle sorte que l'ensemble soupape de sortie (100) est normalement fermé ;

la soupape de sortie s'ouvrant de manière passive sous pression.

12. Injecteur de carburant selon l'une quelconque des revendications 1 à 11, comprenant un système de commande et une bobine électromagnétique configurée pour déplacer le piston (17).

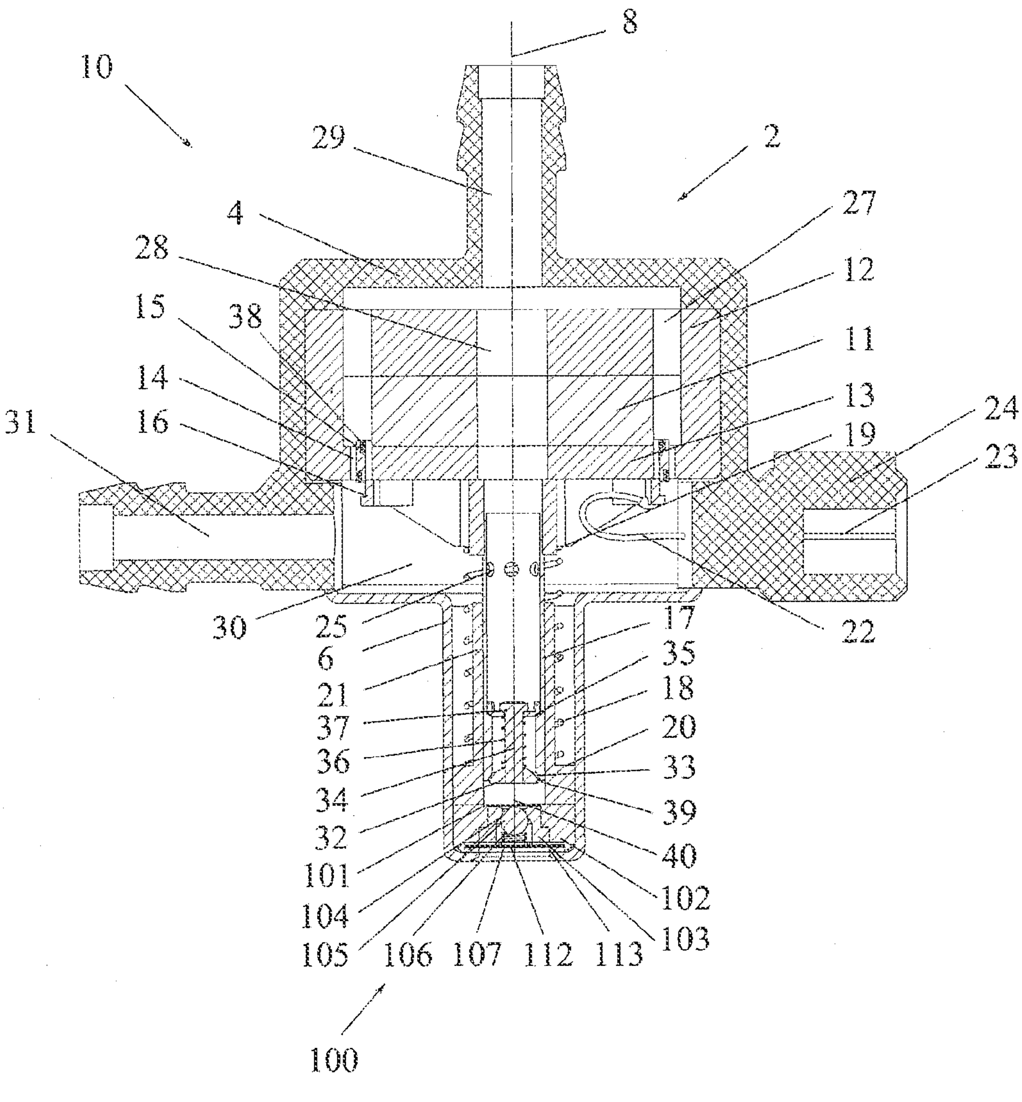
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FIG. 1

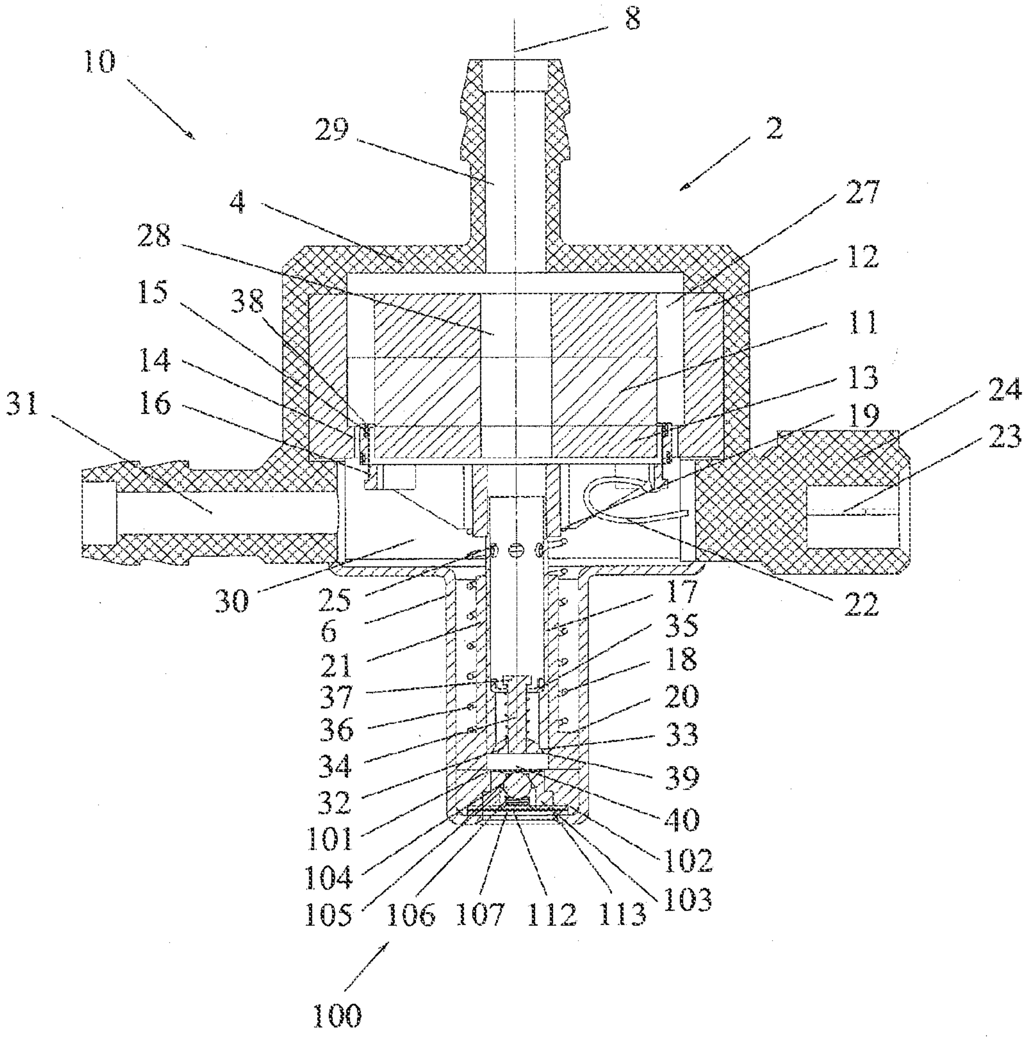
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FIG. 2

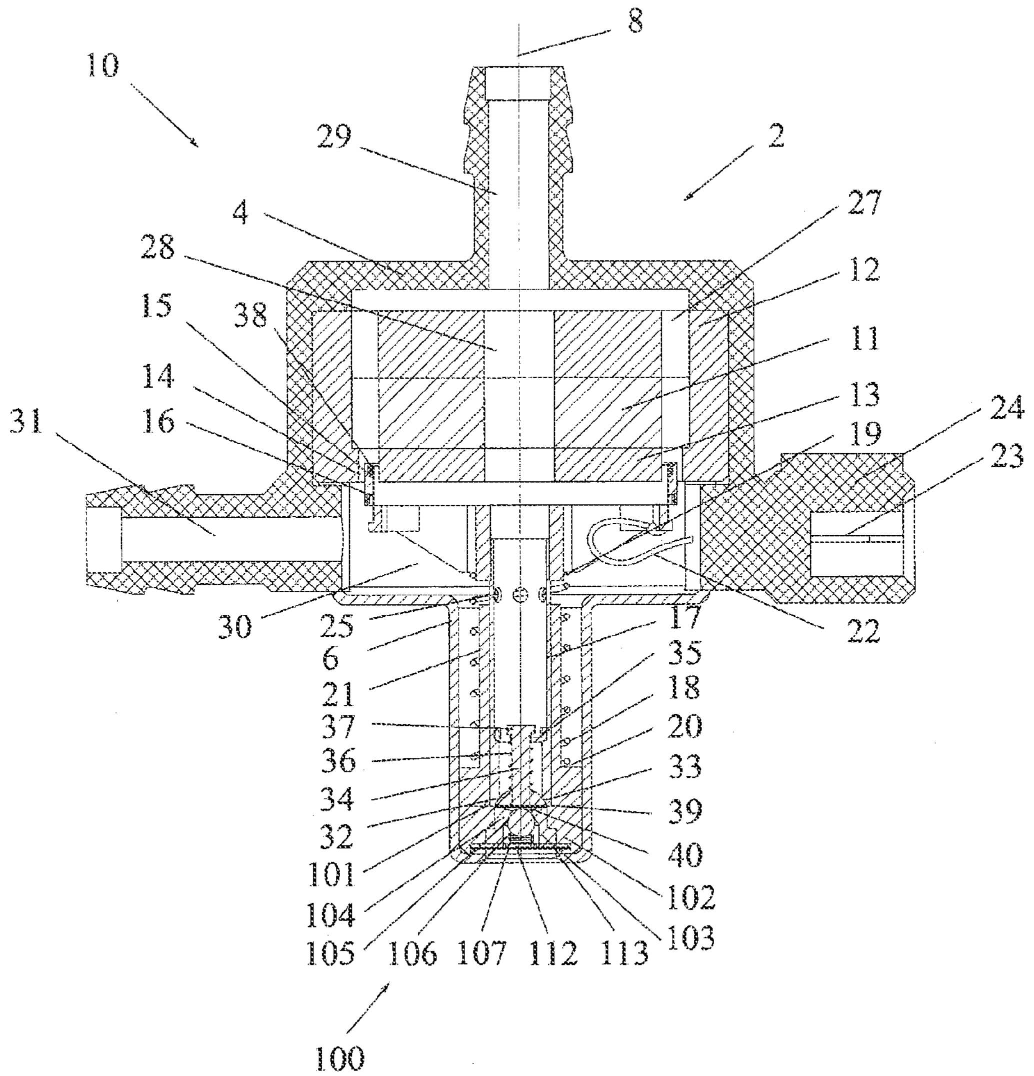
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FIG. 3

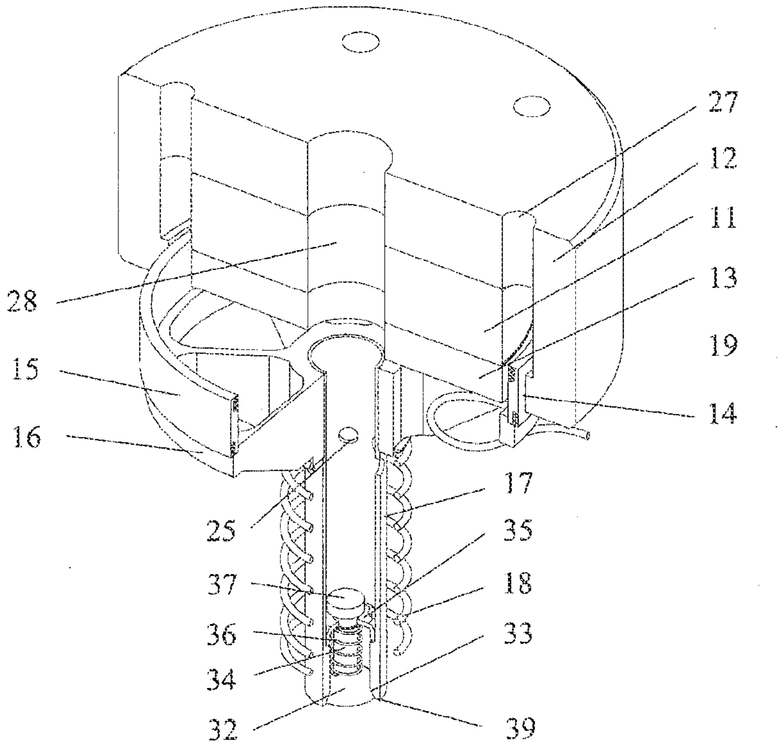
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FIG. 4

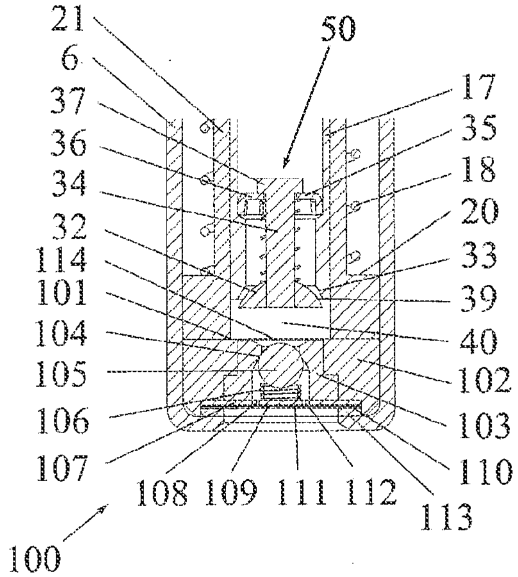
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FIG. 5

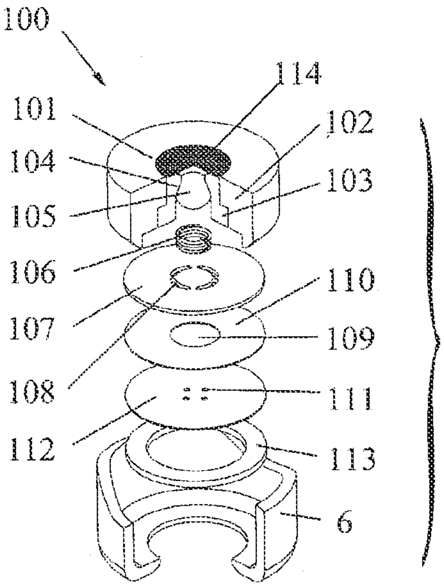
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FIG. 6

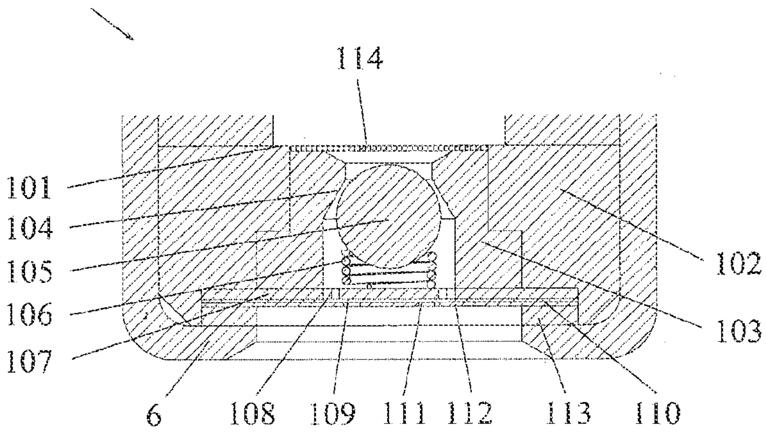
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FIG. 7

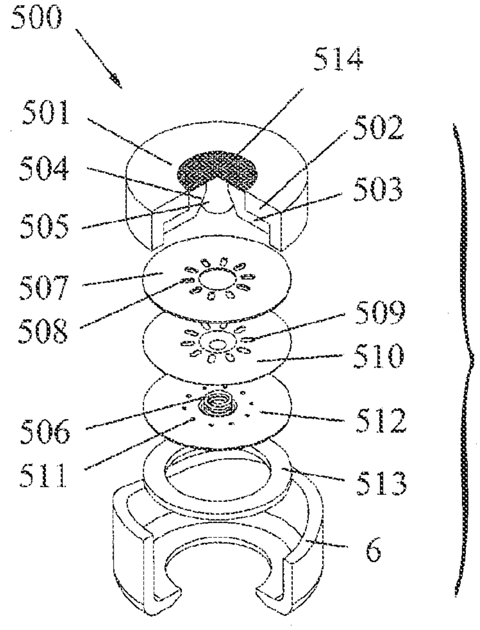
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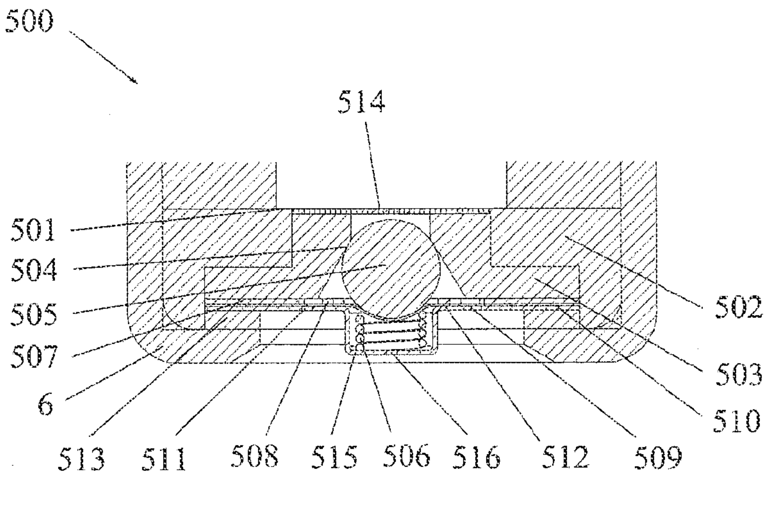
FIG. 8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509

FIG. 9

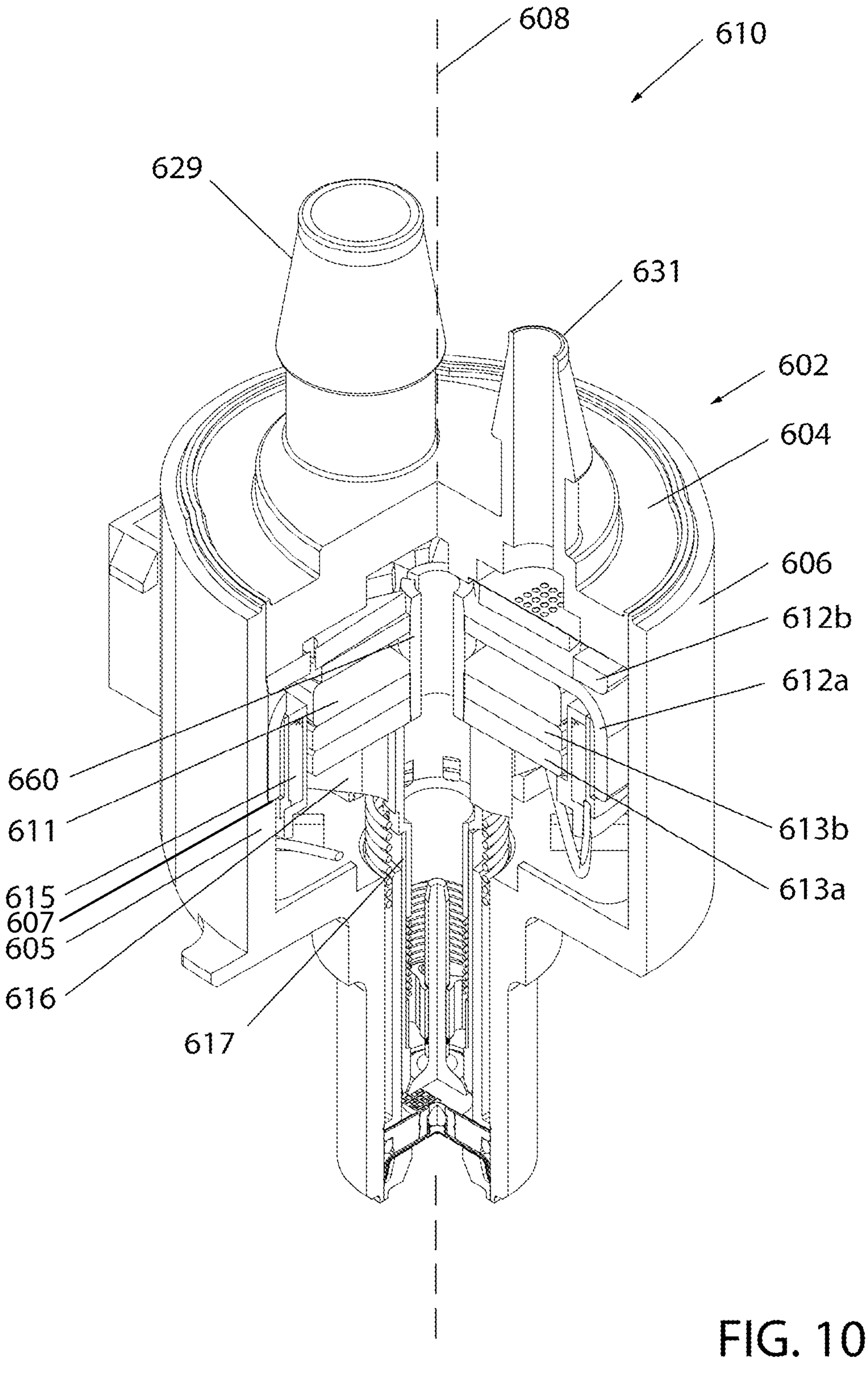

608
610
629
631
602
604
606
612b
612a
660
611
613b
615
607
605
616
613a
617

FIG. 10

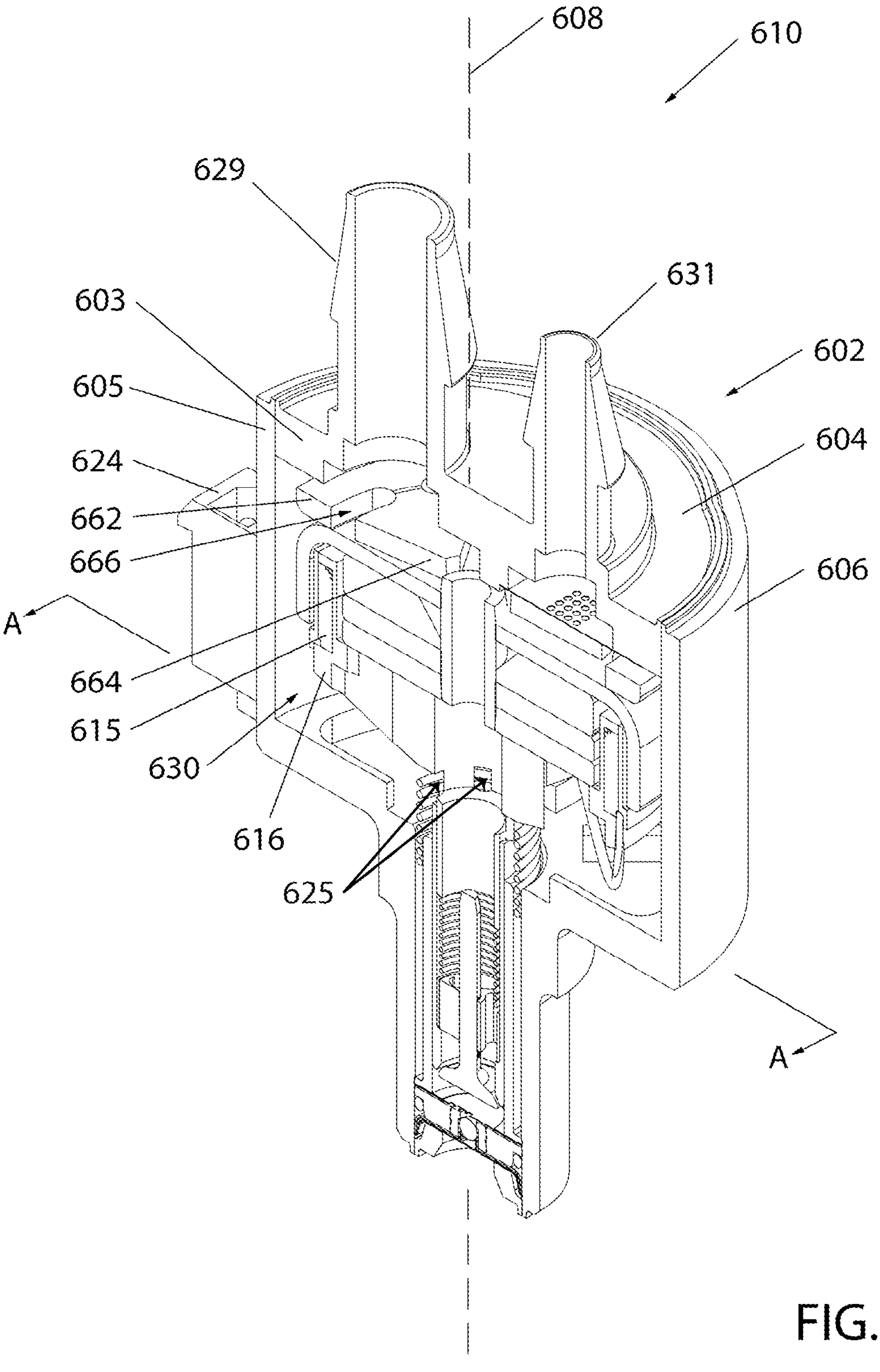

608
610
629
631
603
602
605
604
624
662
666
606
A
664
615
630
616
625
A

FIG. 11

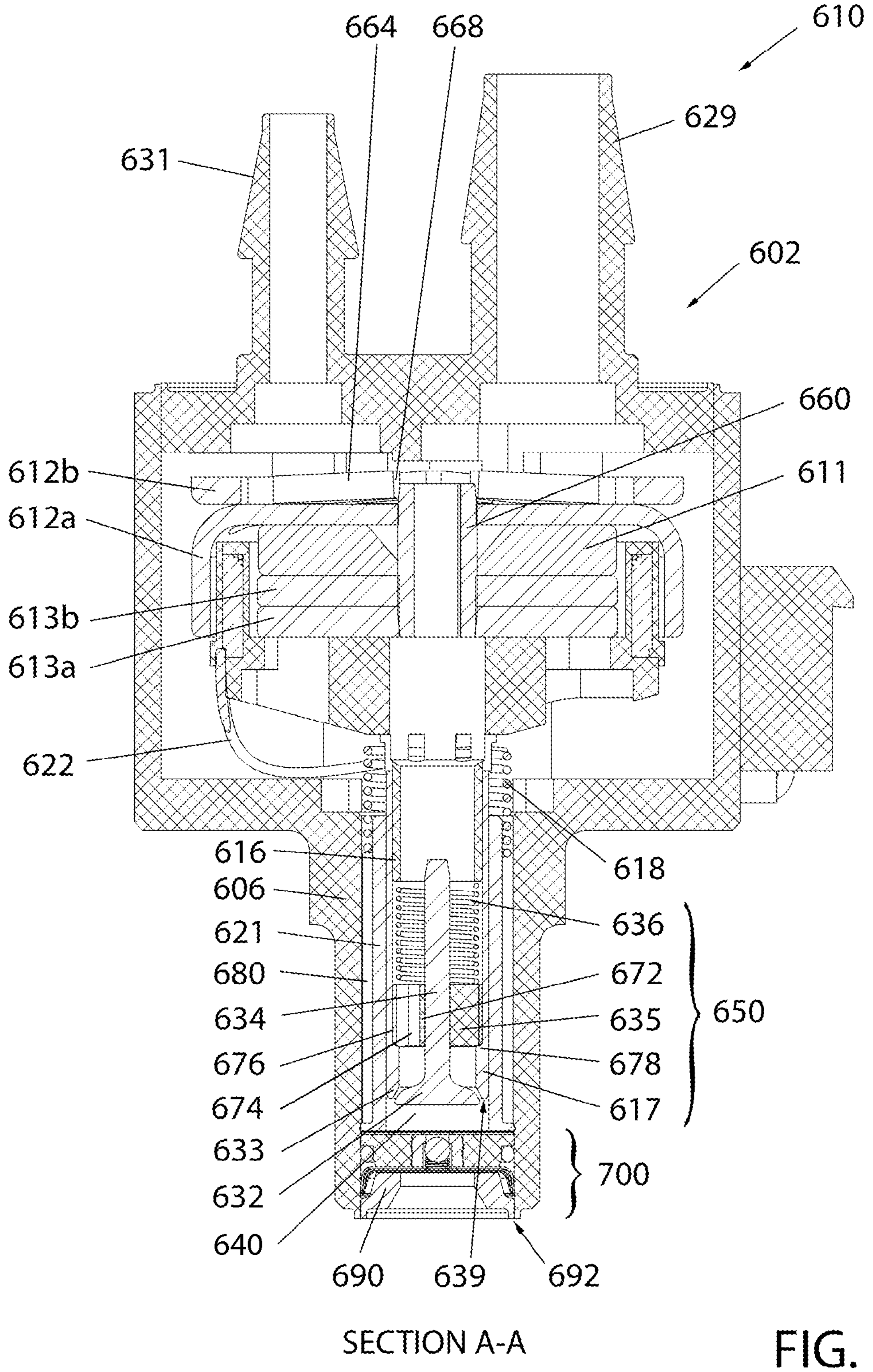

610
664
668
631
629
602
660
612b
611
612a
613b
613a
622
616
618
606
636
621
650
680
672
634
635
676
678
674
617
633
700
632
640
690
639
692
SECTION A-A

FIG. 12

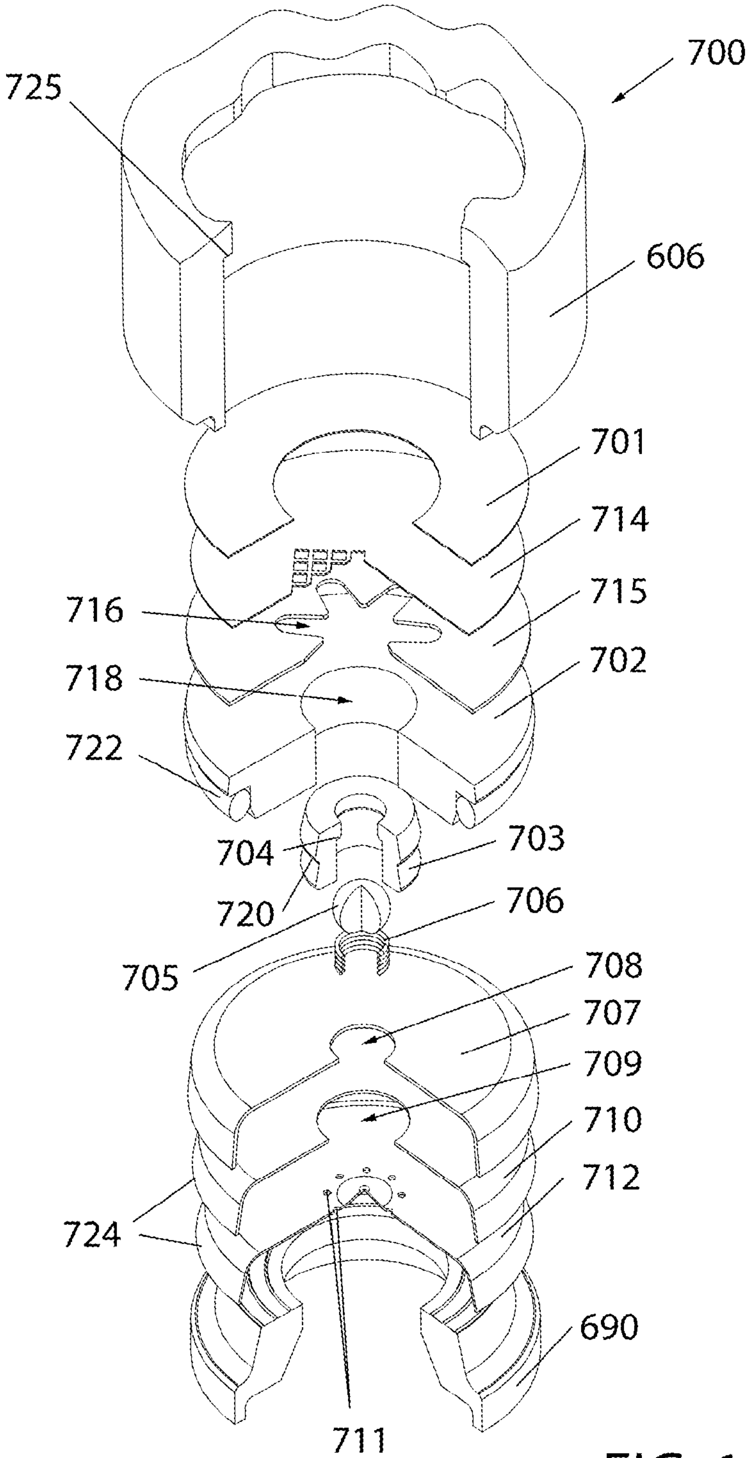
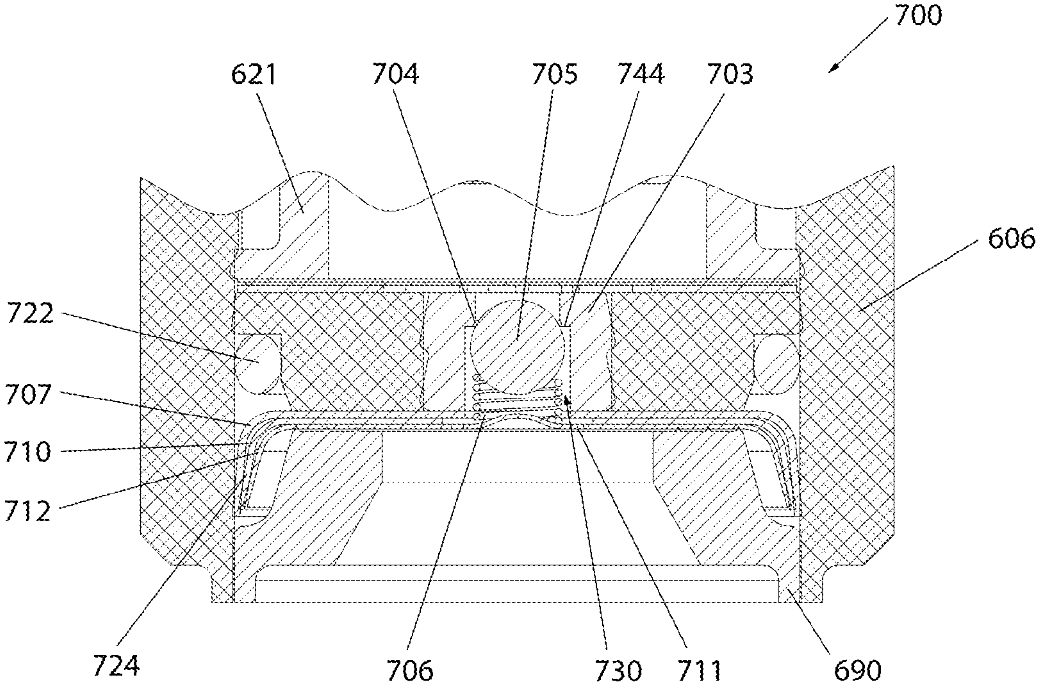

700
725
606
701
714
716
715
718
702
722
704
703
720
706
705
708
707
709
710
724
712
690
711

FIG. 13



SECTION A-A

FIG. 14

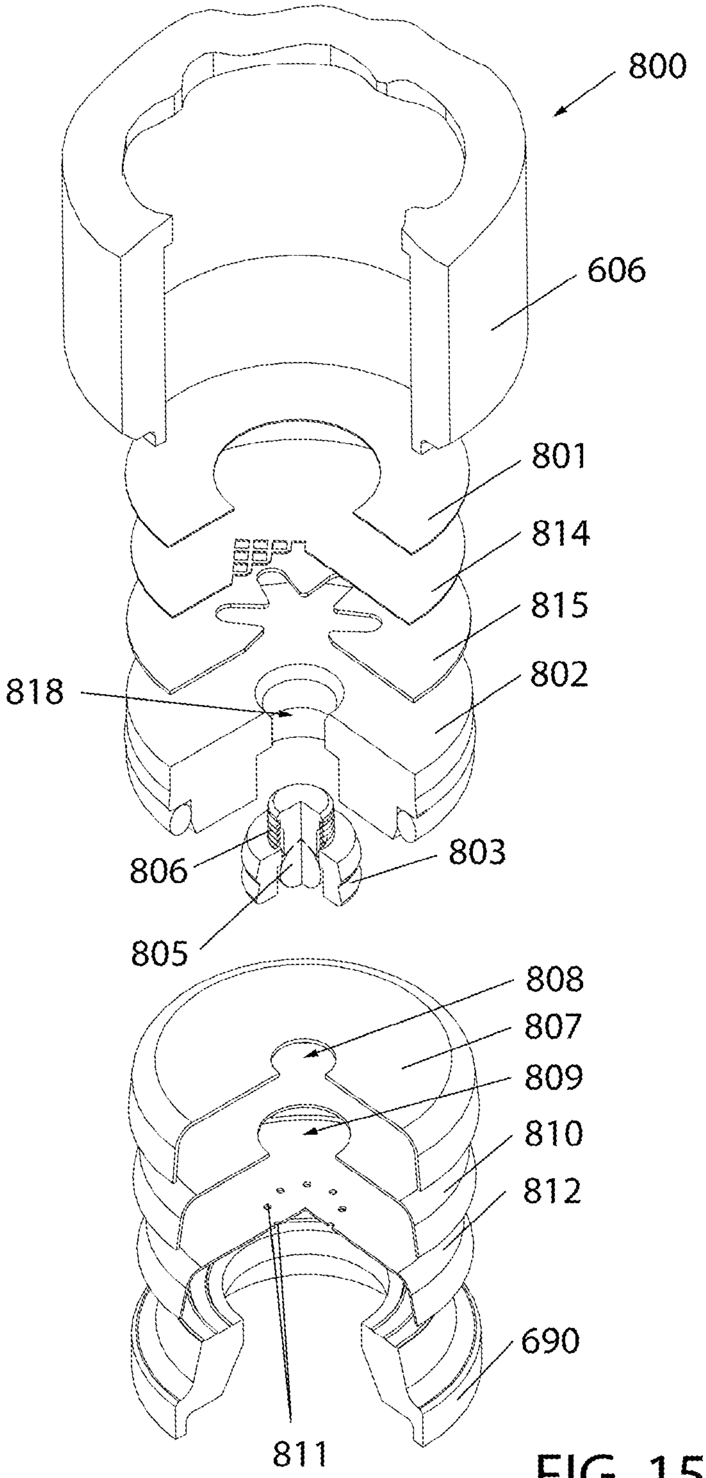
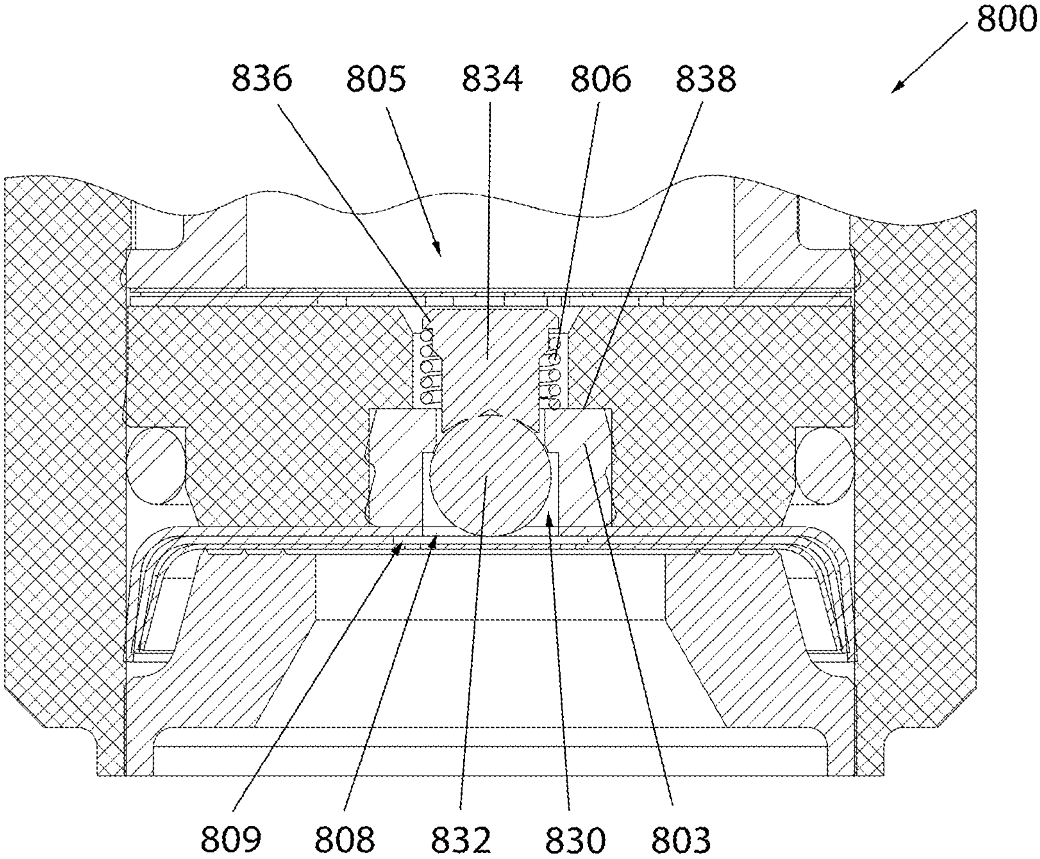

800
606
801
814
815
818
802
806
803
805
808
807
809
810
812
690
811

FIG. 15



SECTION A-A

FIG. 16

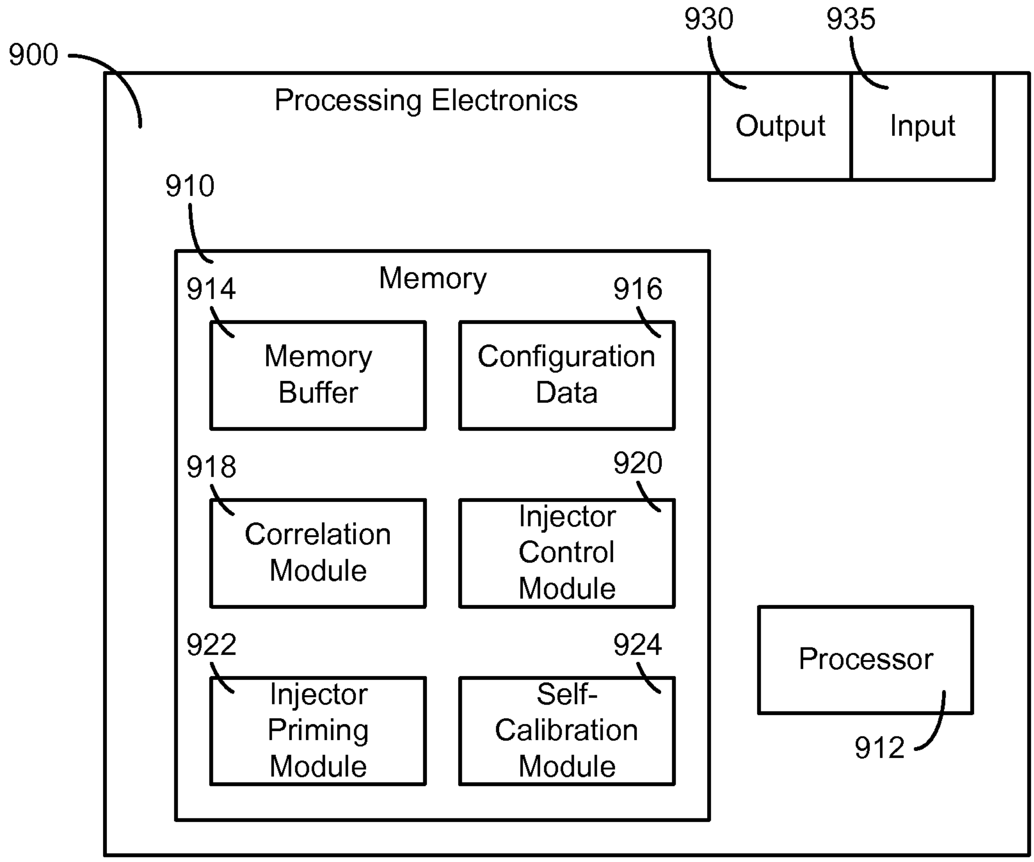

900
930
935
Processing Electronics
Output
Input
910
Memory
914
916
Memory Buffer
Configuration Data
918
920
Correlation Module
Injector Control Module
922
924
Injector Priming Module
Self-Calibration Module
Processor
912

FIG. 17

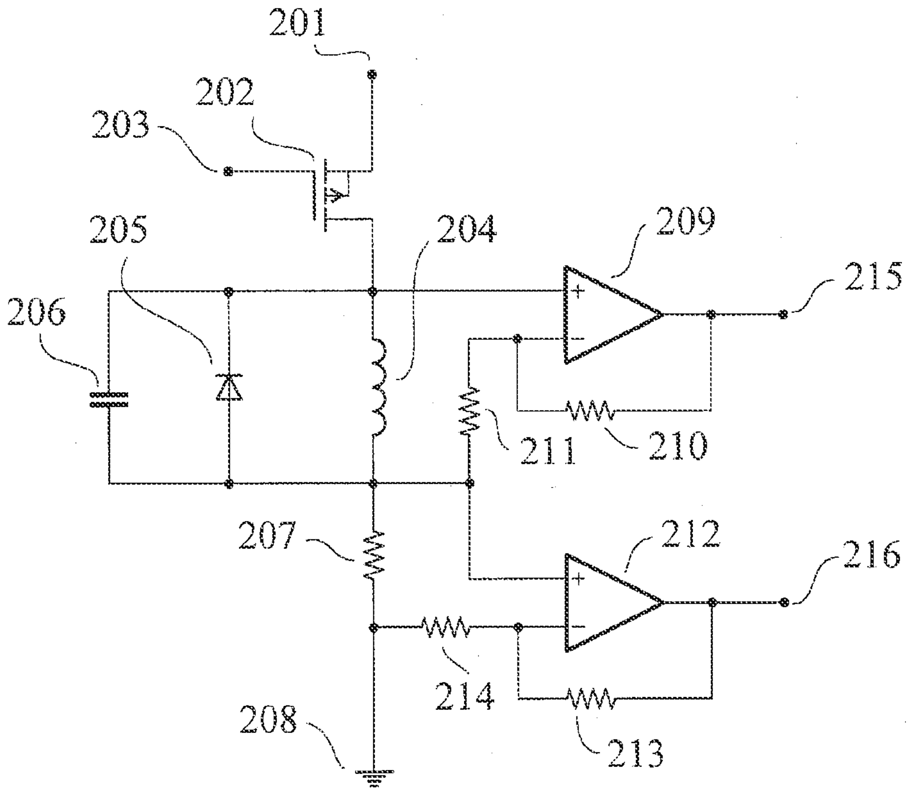


FIG. 18

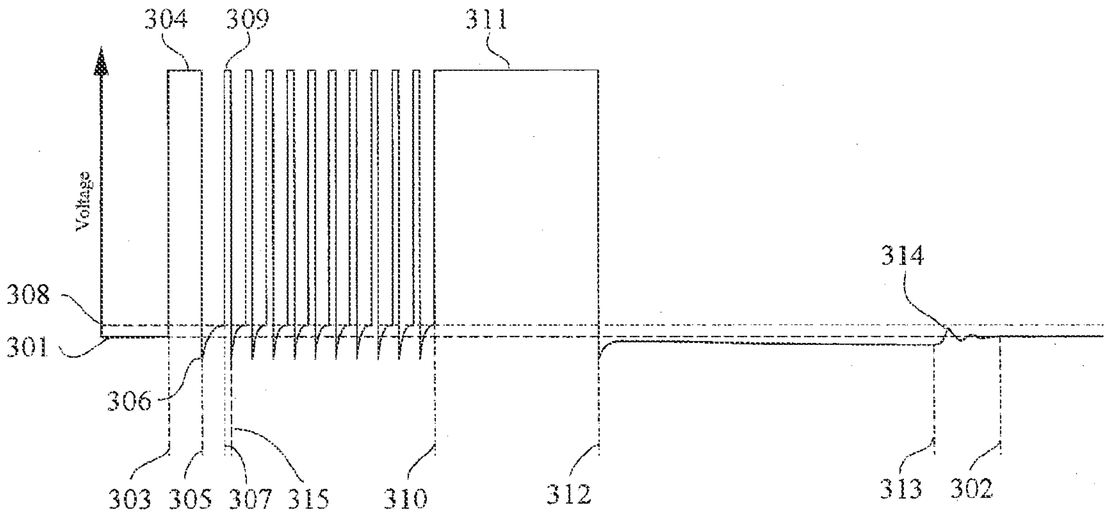

304
309
311
Voltage
314
308
301
306
303
305
307
315
310
312
313
302

FIG. 19

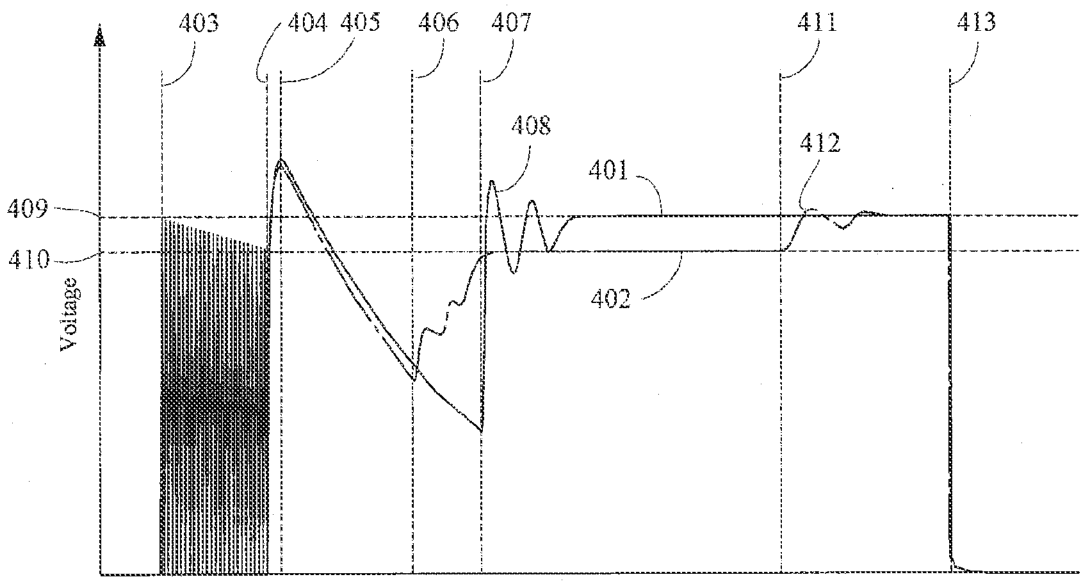

403
404
405
406
407
411
413
408
401
412
409
410
Voltage
402

FIG. 20

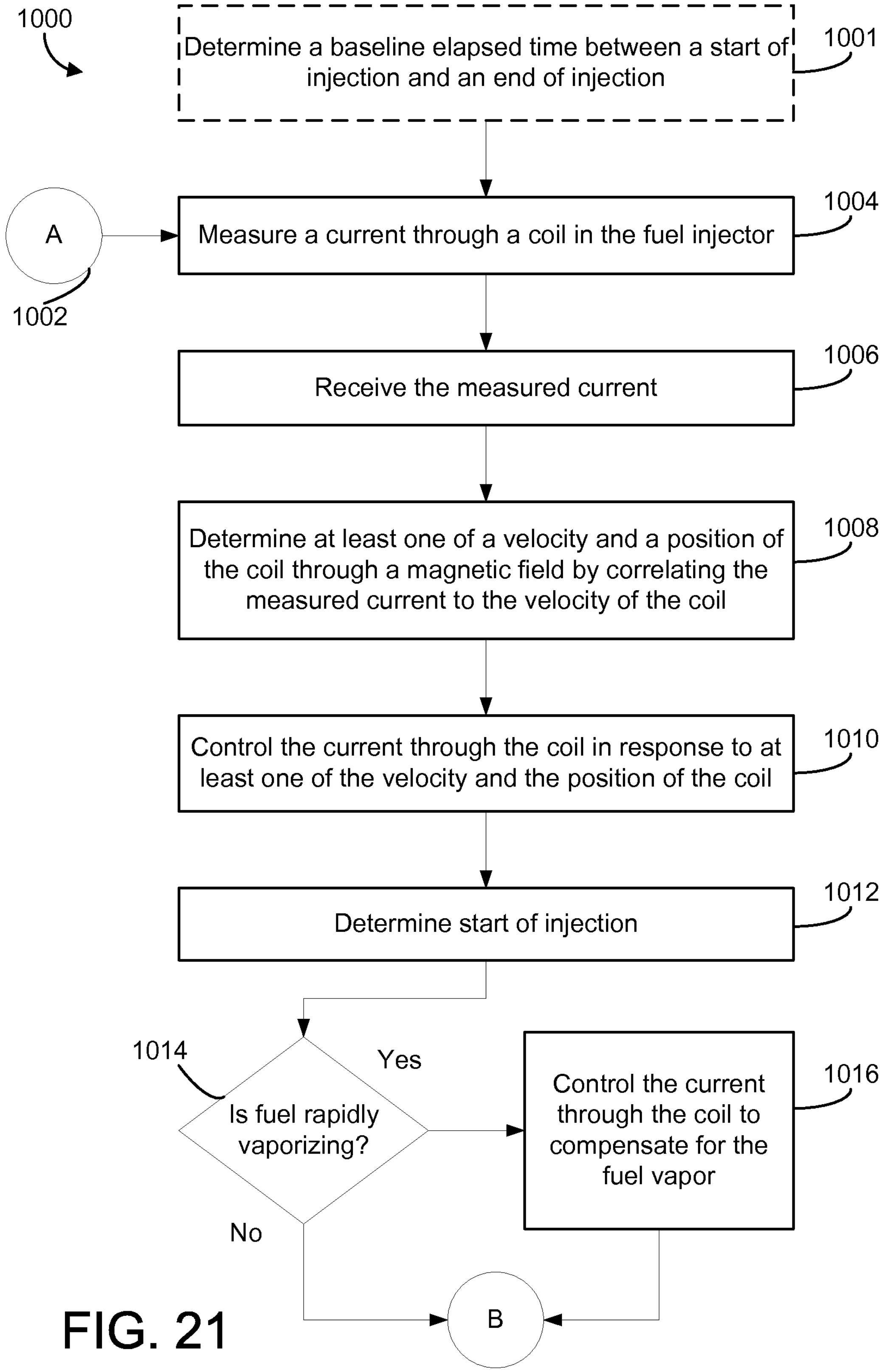

1000
Determine a baseline elapsed time between a start of injection and an end of injection
1001
A
1002
Measure a current through a coil in the fuel injector
1004
Receive the measured current
1006
Determine at least one of a velocity and a position of the coil through a magnetic field by correlating the measured current to the velocity of the coil
1008
Control the current through the coil in response to at least one of the velocity and the position of the coil
1010
Determine start of injection
1012
1014
Is fuel rapidly vaporizing?
Yes
No
Control the current through the coil to compensate for the fuel vapor
1016
B

FIG. 21

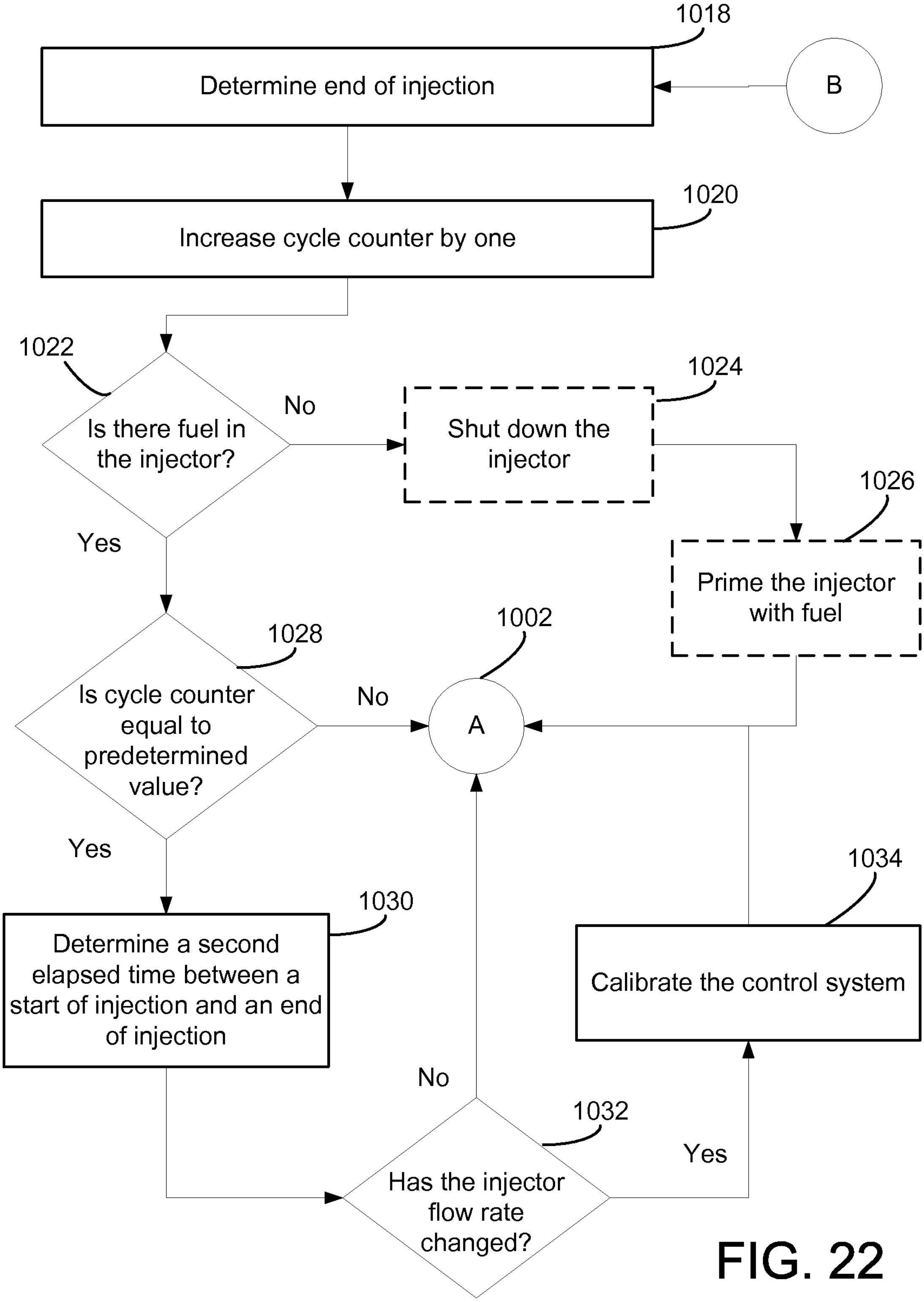

1018
Determine end of injection
B
1020
Increase cycle counter by one
1022
Is there fuel in the injector?
No
1024
Shut down the injector
1026
Prime the injector with fuel
Yes
1028
Is cycle counter equal to predetermined value?
No
1002
A
Yes
1030
Determine a second elapsed time between a start of injection and an end of injection
1034
Calibrate the control system
No
1032
Has the injector flow rate changed?
Yes

FIG. 22

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US 6422836 B1 **[0003]**